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Applied Optics

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COVER: Thomas Young's classic two-slit interference experiment performed with a coherent light source. The slits are openings directly in the silver on one end of the ruby rod of an optical maser, which is shown at the lower left. Coherent light from the two slits interferes to produce the pattern of red dots on the screen. The broad maxima are produced by diffraction from the individual slits. Photograph by J. W. Ammons and R. J. Collins, Bell Telephone Laboratories.

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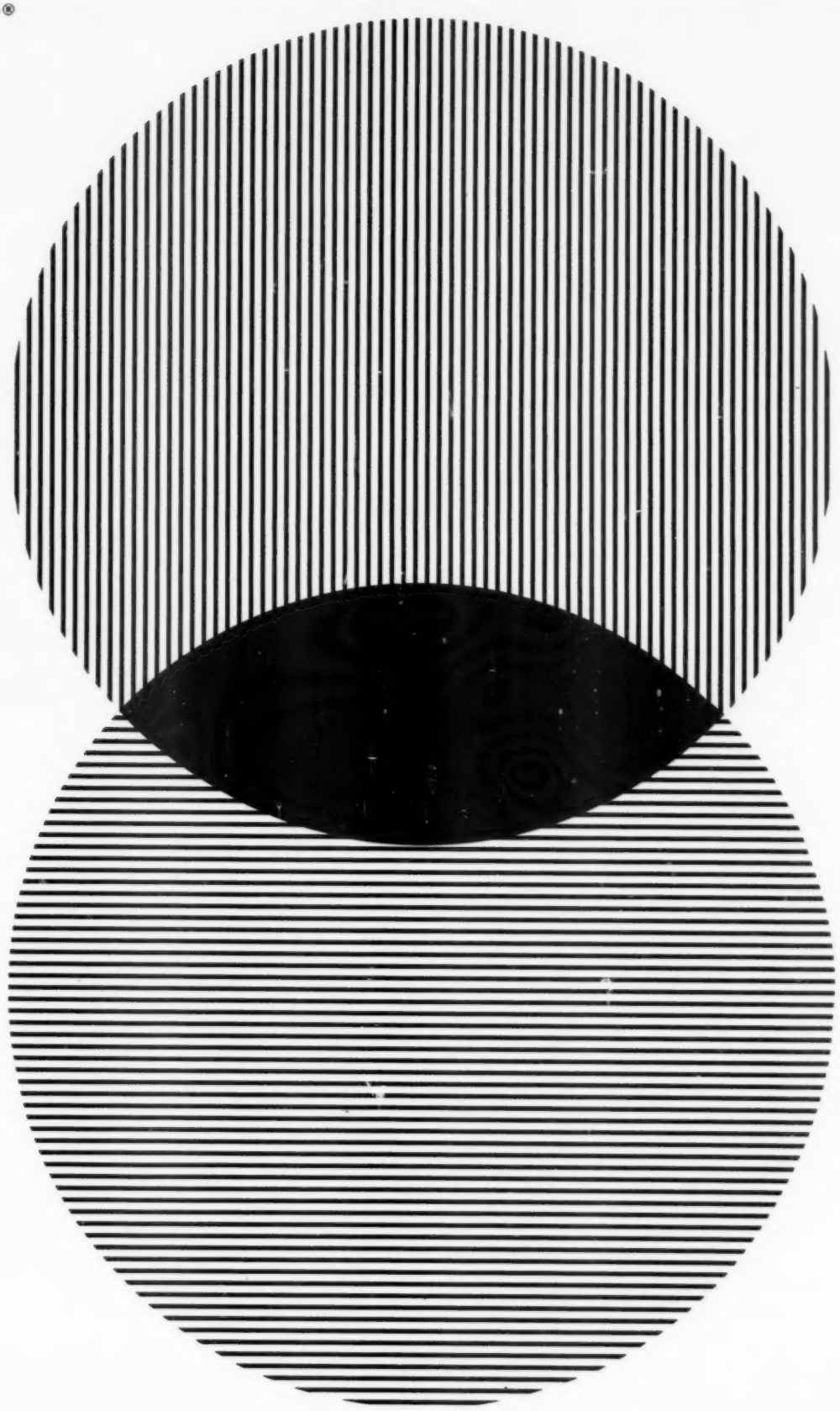

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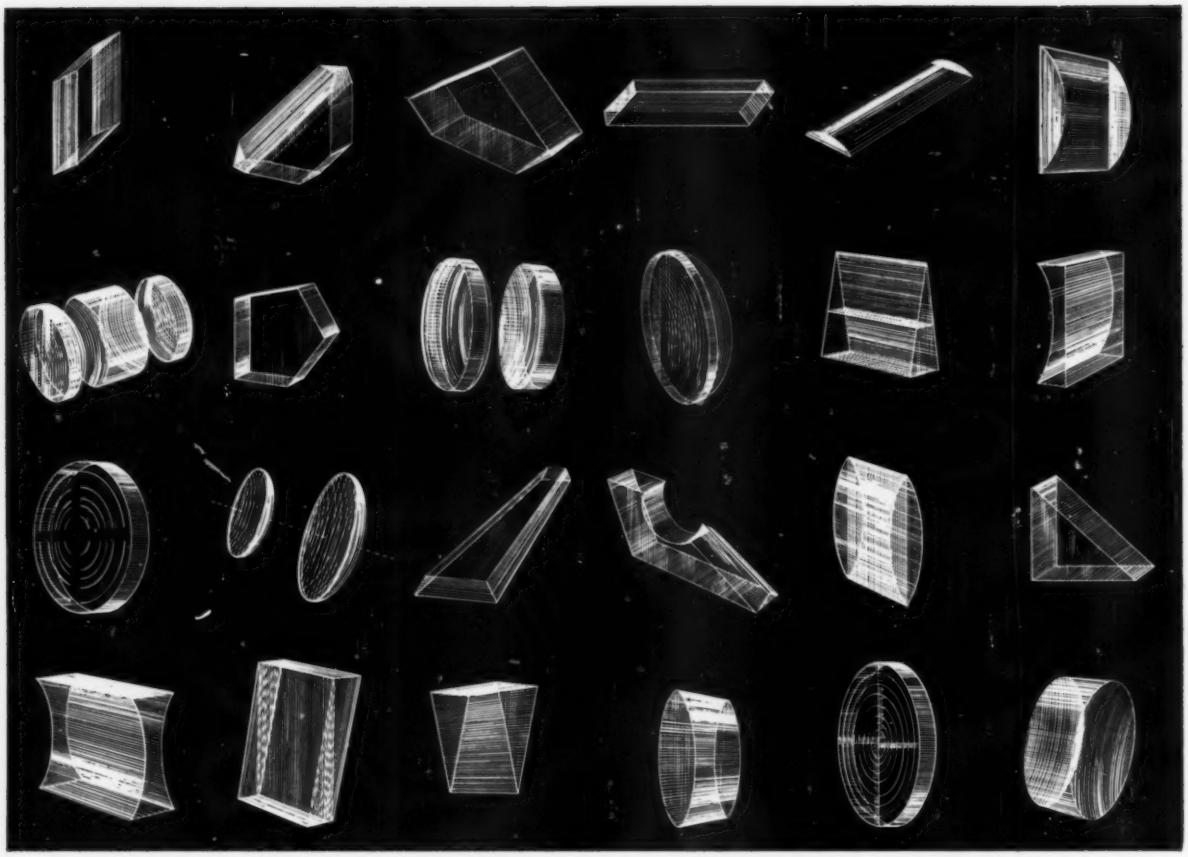

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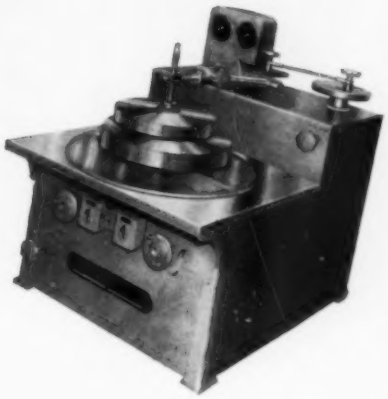

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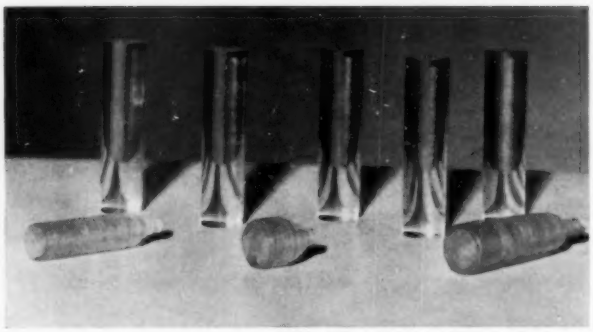

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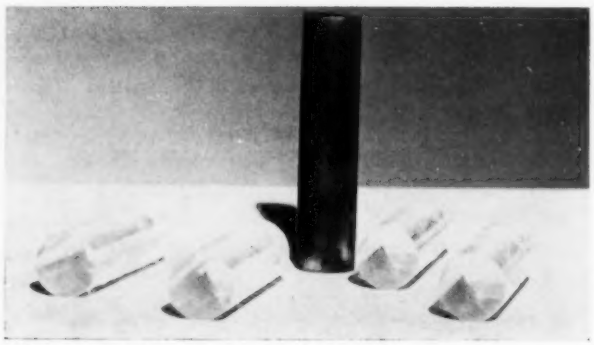

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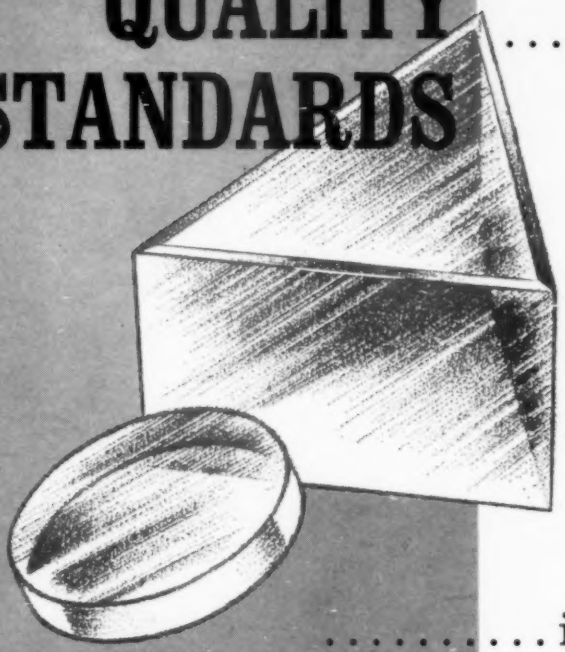

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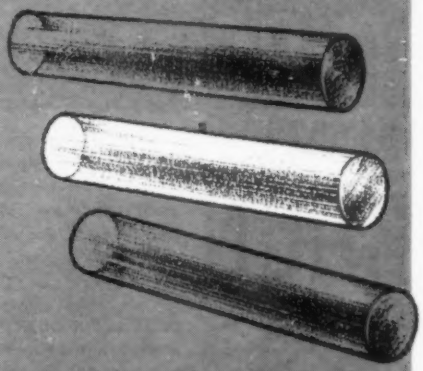

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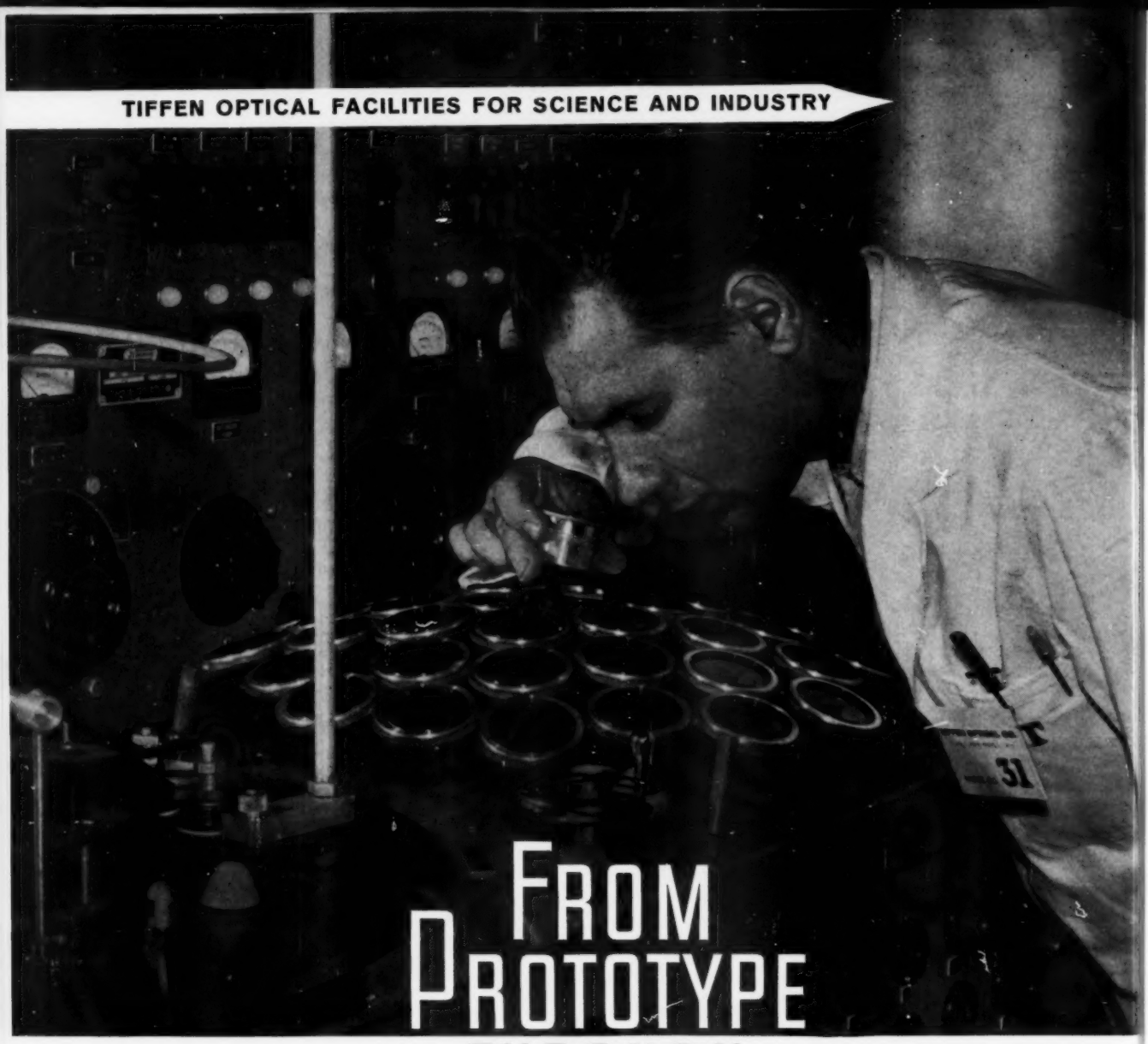

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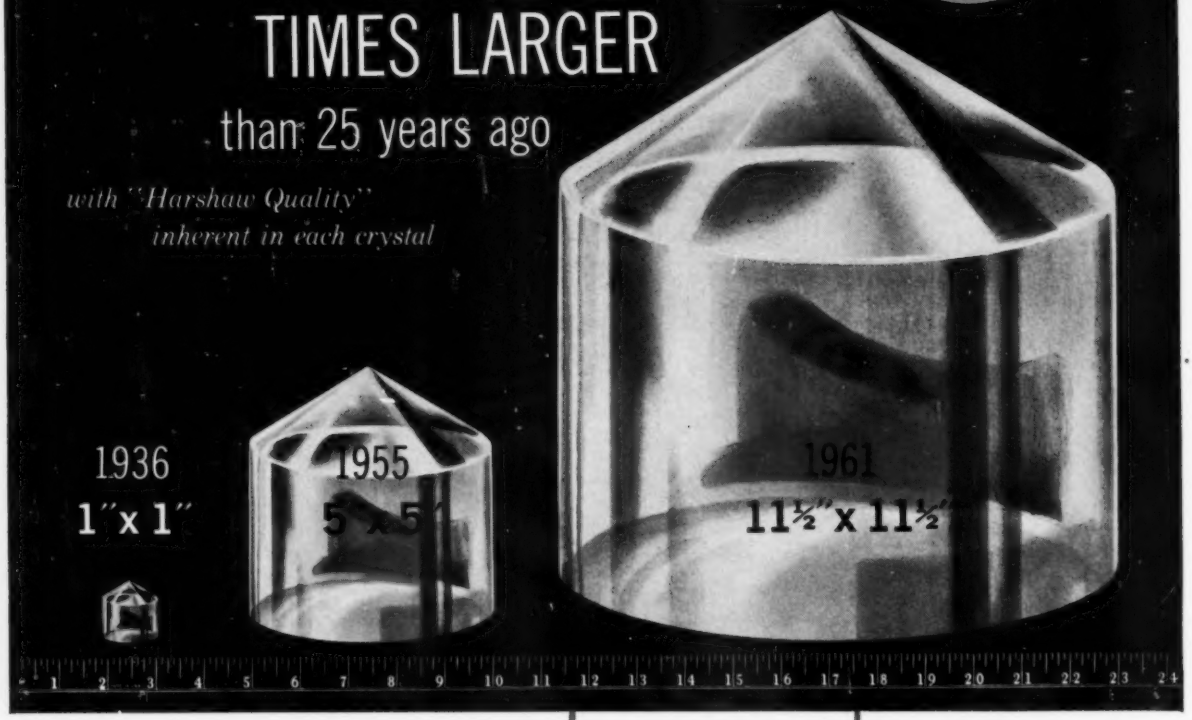

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Magnetic Resonance in Radiating or Absorbing Atoms

F. Bitter

In the last ten years a great deal of work has been done on the experimental investigation of atomic energy levels using magnetic resonance techniques. This paper concerns itself primarily with a review of some of the studies of atomic vapors in connection with level structures, on the one hand, and the mutual interactions of light oscillating magnetic fields and the effects of collisions, on the other.

I. Introduction

This subject, now just over ten years old, appears to merit attention and review for three main reasons: (1) It makes possible the precise investigation of the detailed structure of atomic energy levels, and requires only very few atoms ($\sim 10^{12}$). This is of particular importance in the investigation of the hyperfine structure of radioactive isotopes. (2) It makes possible detailed investigation of the processes of radiation and absorption of light, by providing observable effects that are due to a known controllable perturbation that is operative *during* optical transitions. In effect, this amounts to saying that the detailed shape of energy levels is becoming more readily accessible for experimental investigation, and so a new facet is being added to our knowledge of atomic structure. (3) Just as magnetic-resonance investigations in solids and liquids have added enormously to our knowledge of how matter is constituted, so it appears most likely that similar investigations in gases, and particularly in plasmas, will prove to be illuminating. Much has already been done by radio-frequency and microwave spectroscopy, on the one hand, and by optical spectroscopy, on the other. It is not clear just how these two techniques can best be combined to study plasmas, but surely the pioneering double-resonance investigation of the imprisonment of resonance radiation will point the way.

This paper is intended to give substance to the assertions made above by putting some of the main steps in the evolution of these ideas into historical perspective and by reviewing illustrative examples of the work that has been done.

The author is with the Department of Geophysics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts.

This work was supported in part by the U.S. Army Signal Corps, the Air Force Office of Scientific Research, and the Office of Naval Research.

Received 18 July 1961.

II. Magnetic-Resonance Techniques

Magnetic resonance involves the reorientation of a magnetic dipole, as a whole, in an external field, or the reorientation of one of the magnetic dipoles constituting an atom with respect to the others. In the former case, transitions are produced between the Zeeman components of an energy level; in the latter, between the fine-structure or hyperfine-structure components. This requires an oscillating magnetic field that will induce transitions from the lower to the upper state involved (absorption of energy from the field by the atom), or from the upper to the lower state (forced emission). Spontaneous emission of magnetic-dipole radiation at these microwave or radio frequencies may be neglected.

During the decade of 1930, Majorana[1] and Rabi[2] discussed magnetic-resonance absorption theoretically, and Rabi and his collaborators[3] detected nuclear magnetic resonance experimentally in atomic beams. In their experiments no differences in populations of these various levels involved in the resonance were required. The trajectory of any atom in the beam is changed by a "flip" from one state to another, and it is this change in the number of atoms following one particular path to a detector which is used to monitor the resonance.

The next step was the detection of magnetic resonance[4–7] in solids and liquids, and also in gases. In thermal equilibrium even closely-spaced nondegenerate energy levels, as, for instance, the Zeeman components of an atom in its ground state, are not equally occupied, and magnetic resonance between such levels will involve the absorption of energy as the slightly more densely populated lower levels are transformed into excited levels. This can be detected directly as a removal of power from the exciting circuit. The resonance effect can also be detected by means other than absorption. An atom in a steady state is accompanied by or surrounded by its own stationary fields, but not

by oscillating fields. This is, in fact, what is meant by a stationary state, namely, that its charge distributions and currents are time-independent. In an electric-dipole transition, however, there is an oscillating dipole, oscillating at the radiating frequency. Similarly, in a magnetic transition there is a precessing magnetic dipole, precessing at the Larmor frequency. Normally, the magnetic dipoles in a sample of matter in thermal equilibrium in a magnetic field will precess around the field direction, but with random phases. The Larmor frequency can therefore be detected only as noise.[8] An applied oscillating or rotating magnetic field at the Larmor frequency can induce a certain amount of coherence between the precessing dipoles, and will result in a precessing magnetization of the order of that produced by the constant field. This precession can be detected by means of a suitably tuned circuit that includes a coil surrounding the sample. The precessing magnetization produces a periodic change in flux linkage, and therefore an emf in the coil. All these magnetic-resonance effects depend on the Boltzmann factor, which determines the slight difference of population of adjacent levels in thermal equilibrium.

Next, Lamb,[9] Retherford, and others investigated the fine structure of various states, including the $n = 2$ level of hydrogen shown in Fig. 1, by using a novel magnetic-resonance technique. This level consists of two P-levels which decay readily to the ground state, and an S-level involving a forbidden transition to the ground state. In an atomic-beam experiment involving excited atoms, only those in the S-state will populate the beam, as the others will have decayed at the outset. By introducing an oscillating magnetic field of the proper frequency at some point along the path of the beam, transitions to the P-states can be induced. These immediately decay to the ground state, and the number of atoms arriving at a detector while still in the excited state is reduced. In this way, the now well-known "Lamb shift" was established.

Finally, the optical methods of detecting magnetic resonance were developed after 1950. A discussion of this work follows a review of certain purely optical aspects of the problem.

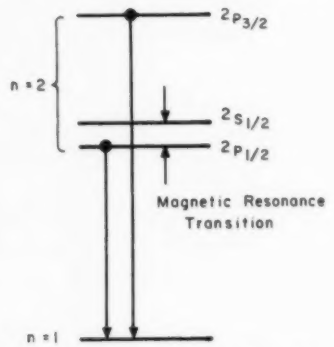

Fig. 1. The fine structure of the $n = 2$ level of hydrogen investigated by Lamb and Retherford, and others.

III. Selective Excitation by Optical Pumping and by Collisions

A prerequisite to the magnetic-resonance investigation of an atomic state is to put a sufficient number of atoms into that state. For most experiments it is desired to excite an atom not only to some one state, but selectively into one of the Zeeman components, or into one of the fine-structure or hyperfine-structure components. No generally applicable techniques for doing this perfectly are at present available, but some of the methods used in the case of mercury resonance radiation may serve to illustrate the possibilities.

The hyperfine structure of the 2536 A resonance line of natural mercury consists of five components of roughly equal intensity separated by approximately two Doppler widths. Some of these components, however, consist of overlapping lines which originate in several isotopes. The details of this structure will be discussed at length below. The first attempts to produce a 2536 A resonance line consisting of one of these components only were made by Mrozowski who used a mercury-vapor filter in a magnetic field, which transmitted one component but absorbed all of the others. At the present time, because of the availability of separated isotopes, lamps radiating single components can readily be constructed. Of the isotopes having even mass numbers (and no nuclear spin), Hg^{198} is the cheapest and commonest, but satisfactory lamps operated by high-frequency electrodeless discharge have been constructed from most of the stable, and some of the radioactive, isotopes. The Hg^{198} lamps are particularly convenient because they radiate, in a magnetic field, just the classical Zeeman triplet (see Fig. 2), of which two components can be eliminated, if desired, by polarization filters. The remaining transmitted line may be "tuned" by varying the field intensity to any desired value for the selective excitation of some one isotope. This technique was first demonstrated[10] in 1953. By noting the absorption in a cell containing mercury vapor as a function of the frequency of the excited light, hyperfine-structure patterns like that shown in Fig. 3 have been obtained[11] for a variety of isotopic mixtures. The resolving power is limited here by the Doppler width of the emission and absorption lines. Work is now in progress in an attempt to increase the resolving power by using atomic beams, both in the emitting and absorbing units.

The magnets used in these magneto-optic scanning experiments were the powerful air-core solenoids of the M.I.T. Magnet Laboratory. These are capable of delivering 60 kgauss in a central tube, 10 cm diam, but at a cost of 1.5 megawatts, or more. An Hg^{198} lamp

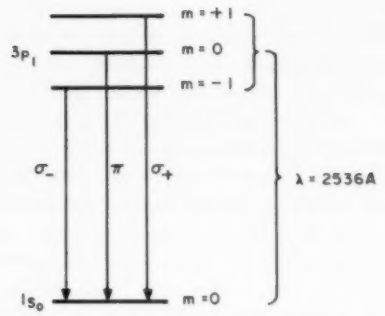

Fig. 2. The Zeeman effect of the $^3P_1$ state of mercury in an isotope having no nuclear spin. The splitting is approximately 2 Mc/gauss. For spectroscopic considerations, this may be put into the more convenient form, approximately 630 10^{-3} cm^{-1} for 10,000 gauss.

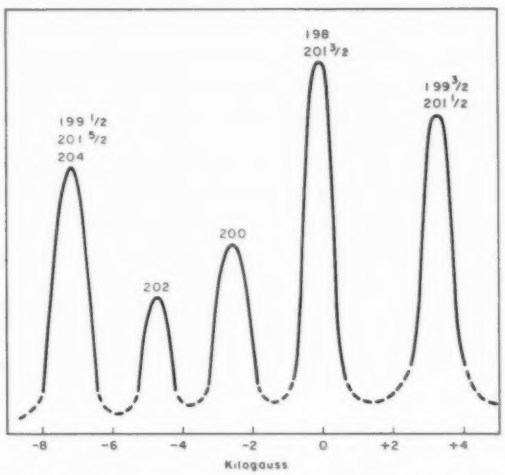

Fig. 3. The hyperfine structure of λ = 2536 A of natural mercury as plotted by magneto-optic scanning.

placed in such a solenoid will radiate only the two circularly polarized σ components in the direction of field, and one of these can be suppressed by using a quarter-wave plate and a polarizing filter. The demands on the laboratory are now such that some other way of producing the required 10 kgauss must be found. Magnets for this purpose are being constructed. It might be mentioned, at this point, that the field of an air-core solenoid of internal radius a_1 in cm, operated at a power level of W watts, is of the order of

$$H \approx 100\sqrt{\frac{W}{a_1}} \text{ gauss.}$$

Thus, to produce 10 kgauss in a tube that is 4 cm in diameter would require only 20 kw. By the use of auxiliary iron, this figure can be further reduced. Quite small magnets, weighing only forty-five kg or so, can be designed for such work. If it is not necessary to extinguish all but one of the Zeeman components, as for example in the selective excitation of an atom at the frequency of one component while the other components are not absorbed, the light may be taken at right angles to the field of an ordinary small iron-core electromagnet.

A most important adjunct in optical selective excitation is the polarization of the exciting light. If it is desired to excite one of the Zeeman sublevels of the $^3P_1$ state of Hg^{198}, shown in Fig. 2, in a field that is so small that the splitting is much less than the Doppler width of the exciting light, this may be done by arranging that the exciting light be plane-polarized, with the electric vector, for instance, parallel to the applied field. This is, in fact, the method used in the first double-resonance experiments.

The term "optical pumping" may well be taken to mean the selective population of any state by optical means. It was first proposed, however, by Kastler[12] in a particularly elegant form in which it was possible not only to equalize the populations of two states by resonance absorption between them, but to force a selective population of a state which can, under certain circumstances, approach completeness. This involves absorption from state 1 to the excited state 2, from which radiation can take place either back to state 1 or to some intermediate state 3, as shown in Fig. 4. If this state is metastable or long-lived, and exciting radiation is sufficiently intense, essentially all of the atoms in state 1 can be transferred to state 3. This condition can be detected by noting the decrease in the absorption of the incident light as the population of state 1 decreases. Population inversions achieved in this way form the basis of the recently invented optical masers.[13] Our interest in this type of optical pumping centers around the production of nuclear orientation or nuclear alignment. In this case the two levels, 1 and 3, correspond to two different orientations of a nucleus in a magnetic field. The levels are almost degenerate, and it is necessary to avoid exciting atoms in state 3 with the same light that excites them in state 1, by making use of polarization conditions. This is illustrated in Fig. 5 for Hg^{199} with a nuclear spin of $1/2$. Circularly polarized light of one sign of rotation can be absorbed only by atoms with their spins in one orientation, and the optical pumping transfers these to the other orientation. The incident light continues to

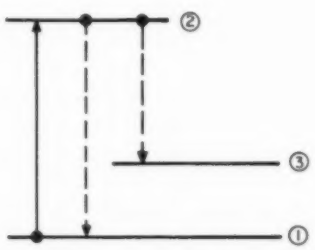

Fig. 4. Optical pumping to an intermediate level.

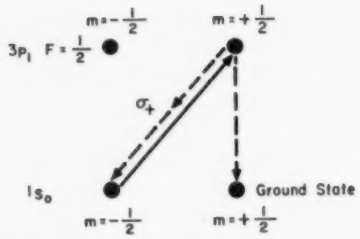

Fig. 5. Optical pumping in Hg^{199} having a nuclear spin of $1/2$ by the absorption of circularly polarized light and excitation to the $F = 1/2$ hyperfine level of the $^3P_1$ state. In the subsequent decay some of the atoms are transferred, or "pumped," into a different m-level.

"pump" until thermal relaxation processes of one kind or another just balance the pumping rate. Distributions with 80–90% of the nuclei pointing in one direction have been achieved in this way.

Selective excitation of the sublevels of higher excited states has been most successfully accomplished[14] by using directed beams of electrons of controlled energy. This is accomplished at low pressures by accelerating electrons from a plane cathode with a nearby plane grid. As the electrons move through the gas or vapor toward the plate, they excite the atoms, and the radiated lines are, in general, polarized; this indicates that the sublevels are not equally populated.

Optical Effects Involving Magnetic Resonance

The first attempts to detect magnetic resonance optically were undertaken by Brossel, at the author's suggestion, more than ten years ago, while he was at M.I.T. These attempts were abandoned, as they were shown by Pryce[15] to be based on a miscalculation.[16] The effects that were sought, which involved a splitting of the radiated lines by the oscillating magnetic field, were too small to detect, being of the order of the Zeeman effect in a constant field of the magnitude of the rf amplitude. Kastler[17] then suggested that effects resulting from induced transitions between sublevels be sought. Soon afterward, the effect was found by Brossel in the $^3P_1$ level of the even isotopes of mercury. By exciting the $m = 0$ level with π resonance radiation (see Fig. 2), the appearance of the σ components in the scattered light could be used as an indication of magnetic resonance. The resonance curves[18] shown in Fig. 6 were obtained. The author was then able to show[19] that the distinctive shape of these resonance curves was due to the multiple degeneracy of the magnetic-resonance transitions in this level with $J = 1$, and could be accounted for by a straightforward application of the Majorana formula for the magnetic-resonance transition probabilities.

This method of using changes in the polarization of the emitted resonance radiation to detect magnetic resonance has been used extensively since that time. Recently, however, two new techniques have been used. One of these, which is due to Kohler,[20] is particularly useful for measuring the distance between levels separated by more than the Doppler line width. One of the two levels whose spacing is to be measured is illuminated by a suitably tuned lamp, and the reradiated light is passed through a filter that absorbs this same frequency. Magnetic-resonance transitions to the second level will alter the frequency of the reradiated light, which can now pass through the filter and be detected by a photocell. This method makes use of a frequency change, rather than a polarization change as in the earlier experiments.

The final method, which is due to Series,[21] makes use of the fact that the light emitted by a precessing atom is modulated at the precessional frequency. In the absence of an externally applied field oscillating at the resonance frequency, there is no phase relationship between the various precessing atoms, but just as in the case of nuclear magnetic resonance in solids and liquids discussed above, the applied rf field produces a certain degree of coherence in the precession of the radiating atoms, and the emitted light is therefore modulated. As is apparent from the form of the Majorana expression for the transition probabilities, when more than two equally spaced levels are involved in a resonance,

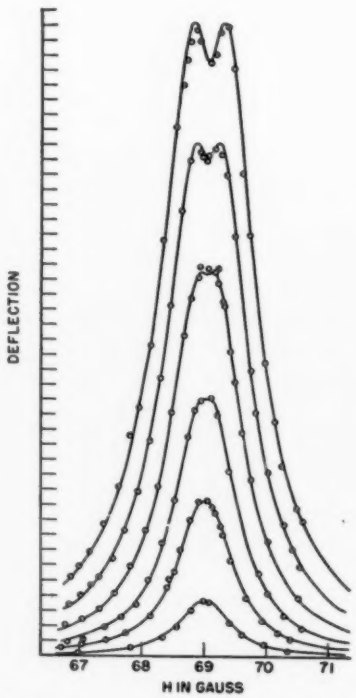

Fig. 6. Double-resonance curves observed in the isotopes of mercury with even mass number, involving magnetic resonance in the excited $^3P_1$ state.

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various multiples and submultiples of the normal Larmor frequency may be expected. The modulation of the resonance radiation emitted by a precessing atom is formally equivalent to a "beat" phenomenon between two coherent radiations whose frequencies differ by the amount of the precessional frequency. For this reason, the above-described method has been termed the method of "light beats."

Magnetic resonance in a state may be monitored by absorption, as well as by emission involving that state. This is particularly important for the measurement of nuclear moments or hyperfine structures in ground states whose sublevels are selectively populated by optical pumping.

IV. Level Structures

The detailed measurement of fine structures and hyperfine structures and other resonant frequencies by the methods of radio-frequency spectroscopy[2] has been of great importance in physics. Outstanding in this connection is the Lamb shift, the anomalous magnetic moment of the electron, the shell structure of atomic nuclei, based in large measure on precise measurements of nuclear moments, and atomic hyperfine structures. We shall focus our attention primarily here on some recent results with mercury, which, so far, have been published only separately, as they illustrate typical examples of double-resonance and related optical experiments.

Results obtained, thus far, are summarized in Fig. 7, which shows the best values for the resonant frequencies of all isotopes measured, plotted with respect to the resonant frequency of Hg^{198}. The shift in frequencies from the 198 isotope is determined primarily by spectroscopic means and is given in units of 10^{-3} cm^{-1} while the separation of the hyperfine structure components is measured directly by magnetic-resonance methods, and is measured and given in Mc/sec. First, let us consider the isotopes of even mass number, and zero spin. Since the lines for Hg^{204} and Hg^{198}, as shown in Fig. 3, are coincident with other lines that are due to Hg^{199} and Hg^{201}, their centers are not necessarily the centers of the desired lines. A double-resonance method has been developed[23] to eliminate this effect by measuring only the change in intensity of re-radiated light when magnetic resonance in the isotopes of even mass number was induced. This, in effect, selects that part of two or more overlapping lines which is radiated by atoms having selected g-factors. This does not, however, eliminate the Doppler width of the lines, and the results are therefore not as accurate as recent interferometric measurements by Schweitzer,[24] who used atomic beams. His values are given for the position of all of the lines that are due to stable isotopes except Hg^{196}, which is normally present at a concentration of only 0.16%, but was prominently present in residues from some of our radioactive samples, and is also available in small quantities in enriched mixtures. These results on isotope shift are considered to be particularly important, especially if the accuracy of the measurements can be improved still further, since they give promise of our being able to investigate the charge distribution within a nucleus with the same detail that the hyperfine-structure anomalies (Bohr-Weisskopf effect) provide for the analysis of the current distribution, or the nonuniform distribution of nuclear magnetization.

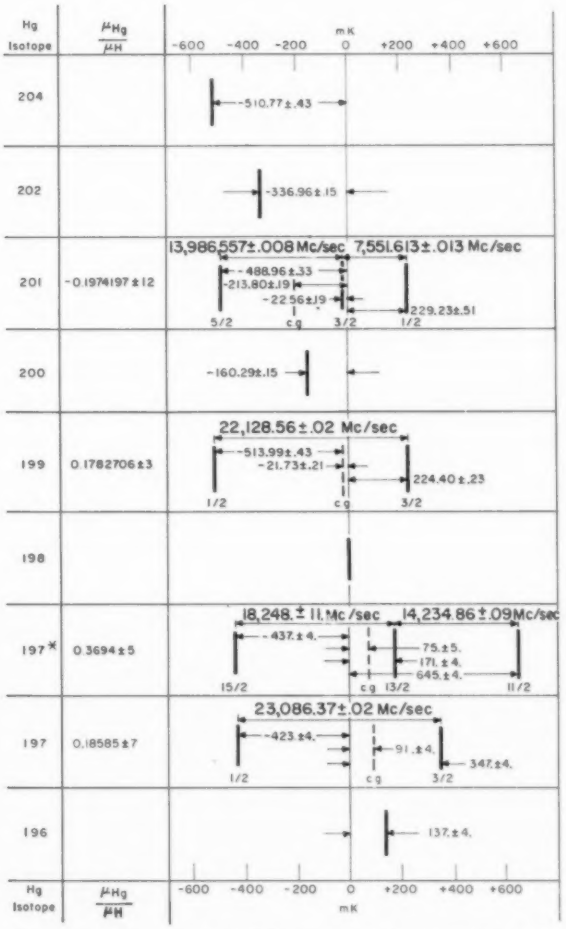

Fig. 7. Summary of available data on the structure of the 2536 A resonance line emitted by various isotopes of mercury. The separations of the various frequencies from the Hg^{198} frequency are given in units of 10^{-3} cm^{-1}. The frequency differences between the radiations from a single atom are given in megacycles per second. The ratios of the nuclear moments to the proton moment are frequency ratios, and are not corrected for the diamagnetic shielding caused by the outer electrons. The data for Hg^{197*} are calculated from the hyperfine structure in the $^3P_1$ state. All other moments are obtained by optical pumping in the ground state.

The hyperfine-structure intervals of the stable nuclei Hg^{201} and Hg^{199} were obtained by Kohler[20] and Stager,[25] with the use of a double-resonance technique involving the change in frequency of the re-radiated light. For Hg^{201}, light from an Hg^{198} lamp was used to excite atoms in the cell to the $F = {}^3/_2$ level, which happens to fall within the line width radiated by the lamp. The re-radiated light was passed through an Hg^{198} filter, and was absorbed until magnetic resonance changed its frequency. For the Hg^{199}, an Hg^{204} emission and absorption lamp was used.

Obtaining the results for the radioactive isotopes, Hg^{197}, and its isomer, Hg^{197*}, was a lengthy process. The first experiments with the use of simple magneto-optic scanning[11] gave a preliminary indication of the structure of Hg^{197}, but it was impossible to identify the lines that were due to Hg^{197*}. The many overlapping lines provided us with too complicated a situation to sort out reliably. It was found that usable electrodeless-discharge lamps could be made, even with the very small quantities of the radioactive isotopes available, and, by using standard spectroscopic techniques involving several spectral lines, Melissinos and Davis[26] were able to make preliminary estimates of the splitting and shift of the 2536 A radiation of Hg^{197*}. With these preliminary values for the hyperfine separations, Melissinos[27] and Hirsch[28] conducted the first successful double-resonance experiments in Hg^{197} and Hg^{197*}. These investigations were made with already existing apparatus, and the resonances were observed in relatively large magnetic fields. To obtain the desired hyperfine splitting, the observed resonances had to be extrapolated back to zero field. Kohler's methods, however, are better suited to precise measurements of the desired quantities directly, or in very weak fields which can be corrected for linearity. These final measurements by Kohler's method are listed in Fig. 7; they were obtained by Stager[29] for Hg^{197}, and for the ${}^{11}/_2 \rightarrow {}^{13}/_2$ transition of Hg^{197*} by Brot.[30] The less accurate value for the ${}^{15}/_2 \rightarrow {}^{15}/_2$ transition is an extrapolation from high-field resonances observed by Hirsch.[28] These included both conventional double-resonance effects, and effects caused by "level crossing" recently reported by Colgrove *et al.*,[31] for the crossing of helium fine-structure lines in a magnetic field, and used here most effectively for the first time for hyperfine-structure determinations.

The hyperfine-structure splittings of the mercury resonance line described above occur in the excited $^3P_1$ state. The ground state, $^1S_0$, with no angular momentum, is diamagnetic, and has no permanent moment except for the very small nuclear moment of the odd-A isotopes. The nuclear moments can best be determined by measuring the Larmor precession frequency in a known externally applied field.

The optical-pumping technique, first successfully applied to alkali atoms,[32] was finally developed in 1958 to the point at which it led to positive results in mercury vapor. This work is summarized in the doctoral thesis of Cagnac,[33] and has led to several important results, some of which are described in this section, and some, relating to depolarizing collisions, in the next section.

The difficulties encountered in earlier attempts to produce nuclear alignment, or orientation, in mercury vapor were due to a variety of causes that took time to track down. First of all, even if wall collisions are not disorienting, the atoms that are being oriented must be isolated from the parent substance to which they will surely adhere and so lose their orientation. Second, the total light flux through the vapor must be as great as possible. In the apparatus used to orient Hg^{199} and Hg^{201} nuclei, a disc-shaped quartz lamp is used, 25 mm diam and 2 mm thick, containing 1 mg of either Hg^{198} or Hg^{204}, with 8-mm pressure of argon. It is excited with a magnetron unit delivering 100 watts at 2400 Mc. The Hg^{204} lamp will excite Hg^{199} to the $F = {}^1/_2$ level, or Hg^{201} to the $F = {}^5/_2$ level. On the other hand, the Hg^{198} lamp will excite Hg^{201} to the $F = {}^3/_2$ level. The light from these lamps falls on the cell in which the optical pumping is to take place in the direction of the magnetic field, and is therefore classed as σ-light, and may be polarized either as σ^+ or σ^-. The orientation produced by the optical pumping in this way can be destroyed by magnetic resonance, and can be detected optically by the change in absorption or scattering of light by the cell. The field, which must be extremely uniform to produce accurate results, can be monitored by a nuclear-resonance probe. The results obtained by Cagnac are:

$$\mu_{199} = (0.1782706 \pm 3 \times 10^{-7})\mu_H$$

$$\mu_{201} = -(0.1974197 \pm 12 \times 10^{-7})\mu_H.$$

At the M.I.T. Magnet Laboratory an effort has been made to provide a variable-frequency light source of sufficient intensity for use in optical-pumping experiments. A disc-shaped lamp of large diameter, approximately 8 cm, in the throat of an air-core solenoid, has recently led to positive results. This is of particular importance in the case of Hg^{197} and Hg^{197*} whose lines do not coincide with those of stable isotopes. A preliminary result obtained by Walter[34] on Hg^{197} is

$$\mu_{197} = (0.18585 \pm 7 \times 10^{-5})\mu_H.$$

This result is less accurate because of the width of the lines obtained in the first version of the apparatus. The resonance in the isomeric state has not, thus far, been detected.

A word of comment may be justified about the effort required to produce the results shown in Fig. 7. They

involve, first of all, the development of optical scanning and atomic-beam techniques, combined with high-resolution spectroscopy. They required the development of very bright and large lamps, of variable frequency in some cases, and of specially designed magnets. They required the development of methods for producing and handling the radioactive samples, of building resonance lamps, and also of electrodeless-discharge lamps containing only very few atoms. Finally, they required the application of microwave techniques with quartz cells within high-Q microwave cavities. The chances of failure in an experiment involving several new and difficult techniques rise very quickly as the number of steps increases, especially if all of the operations involved must take place without failure during the limited lifetime of radioactive isotopes. The successful methods of procedure have, in the main, been described in detail in the theses and publications of the various authors cited. Further work is in progress on (1) other isotopes, (2) the factors governing the useful life of electrodeless lamps and hollow-cathode lamps containing very few atoms, (3) the development of magnets especially suited to this work, and (4) the development of atomic-beam techniques, especially for magneto-optic scanning. A special word of appreciation is due to Henry H. Stroke, whose name has not appeared in this discussion, but who, in fact, has contributed more than anyone else to the success of the experimental part of the work carried out in the M.I.T. Magnet Laboratory, to an understanding of its significance for nuclear-structure theory, and to the maintenance of a spirit of eager interest among the M.I.T. students and staff over a long period of discouraging failures and partial successes. The friendly cooperation and extensive exchange of information with other laboratories, especially the Laboratoire de Physique of the École Normale Supérieure, is also gratefully acknowledged.

Optical pumping in the alkalis promises to be of considerable practical importance, in addition to the theoretical importance of the results of hyperfine-structure measurements of various isotopes in several states by atomic-beam, as well as double-resonance, techniques.[22] Dehmelt's investigations,[35] starting with investigations of relaxation times and the orientation of free electrons by collisions with oriented sodium atoms, led to proposals by Bell and Bloom[36] for the use of magnetic resonances in optically pumped vapors as frequency standards, and as indicators in weak-field magnetometers. Magnetic resonances can be monitored in optically pumped alkali vapors by the absorption of the pumping beam, or by an independent separate beam traversing the pumped vapor. In transitions of the type $m_1 = 0 \rightarrow m_2 = 0$, $\Delta F = 1$ the resonant frequency is practically field-independent in weak fields, and can be used as frequency standards under some conditions, for instance, with not too strong light[37] and not too strong radio frequency,[38] to avoid the various shifts that have been discovered. Other transitions are field-dependent, and may be used in weak-field magnetometers.

V. Transitions

In addition to the results already cited, several interesting effects involving optical transitions have been investigated in detail, particularly at the Laboratoire de Physique of the École Normale Supérieure, in Paris, during the last decade. It is not possible to do this work justice here, but at least some illustrative examples will be presented and an effort will be made to indicate some particularly intriguing aspects of the results obtained.

The first deals with the imprisonment of resonance radiation. Instead of involving the emission and absorption of a quantum in a series of independent events, it has been found that phase coherence among several participating atoms may be maintained by the electromagnetic field in which they are resonating, and that this can be studied by double-resonance techniques.

It has been found[39] that double-resonance curves, such as those shown in Fig. 6, are materially modified as the mercury vapor pressure is changed, and this in a range of pressures so low that atomic collisions are surely not responsible. At very low pressures, below 0.1 μ, or so, they have the form shown in Fig. 6, but at higher pressures they become narrower, and their shape is modified. This can be accounted for by considering the interaction of the atoms with the electromagnetic field. The many papers dealing with this subject are summarized by Barrat[40] who succeeds in developing a theory in spite of the inherent complexity of the problem. It is not surprising that such effects exist, or that imprisonment produces a narrowing of the resonance levels, but it is both surprising and gratifying to find that explicit theoretically-based formulations are possible. The limiting half-width of the resonance curves, $\Delta\omega/2$, at low rf power specifies a time $T = 2/\Delta\omega$ which Barrat calls the coherence time. At low vapor pressures, at which the probability of a quantum being absorbed more than once before escaping from the cell is negligibly small, T approaches τ, the natural lifetime of the excited state. When the vapor pressure is increased, that quanta will, on the average, be absorbed more than once before escaping; T is greater than τ and the line shape is altered. Figure 8 shows results obtained in a series of measurements of T on cells in which resonances in Hg^{202} and Hg^{198} were observed as a function of vapor pressure with varying atomic concentrations of isotopes in the cell. As is to be expected, if this is indeed an effect caused by imprisonment, the concentration of resonating atoms alone determines the coherence time. The calculation for

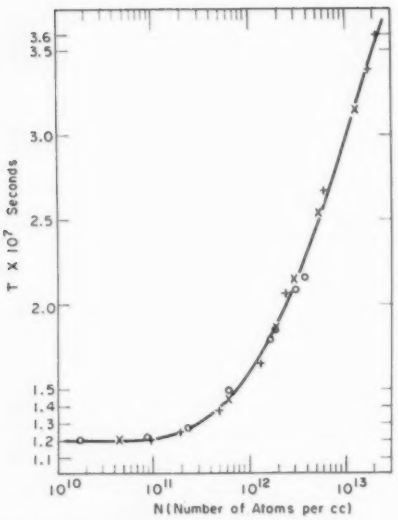

Fig. 8. "Coherence time" of imprisoned mercury resonance radiation in a 2.5-cm³ cell as a function of N, the number of atoms/cm³ of the isotope in which resonance occurs. The points are experimentally measured inverse line widths, and the curve is based on Barrat's theoretical predictions. ○—Hg^{198} resonance radiation in a cell containing natural Hg; ×—Hg^{202} resonance radiation in a cell containing natural Hg; +—Hg^{202} resonance radiation in a cell containing Hg^{202} only.

odd-A isotopes is more involved, but equally in accord with experiment. The depolarization of imprisoned resonance radiation[40,41] can also be taken into account.

We have a important new experimental technique for studying radiating atoms, and likewise an important theoretical method of analysis to help us understand the results. The technique used does not lend itself to the study of imprisonment at higher vapor pressures and in larger cells, since the resonance radiation is largely depolarized, and the small changes resulting from magnetic resonance will then be difficult to detect. Other means of observing the magnetic-resonance curves should be sought, so that the interaction between radiating atoms may be studied more in detail as a function of their number, the distance between them, and, as we shall discuss below, with the effect of collisions on this interaction included.

Another class of experiments deals with excitation by multiple quanta. This is a subject that has been studied theoretically for many years,[42] and has been found experimentally in atomic-beam experiments,[43] as well as in double-resonance experiments.[44]

The conditions of conservation of energy and angular momentum are illustrated in Fig. 9, taken from a note by Margerie and Brossel.[45] These transitions were found experimentally between adjacent Zeeman levels in the ground state of sodium, as shown in Fig. 10. The curves are for three different intensities of the 1206 Mc/s field. At low intensity, the resonances are

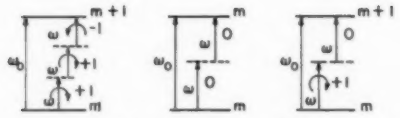

Fig. 9. Possible multiple quantum transitions between adjacent levels.

sharp and only the single and double quantum resonances occur. At the higher fields, the resonances broaden, are shifted in frequency because of the Bloch-Siegert effect,[38] and resonances involving three and four quantum transitions appear. An intermediate level that does not coincide with the intermediate double-quantum jump, as shown in Fig. 11, modifies the resonance curves. Blamont and Winter[46] investigated this case theoretically and experimentally. The three Zeeman levels of the $^3P_1$ state of mercury for isotopes of even-A, shown in Fig. 2, are equally spaced. But if an electric field is applied, the central level, $m = 0$, is shifted by a variable amount ϵ with respect to the other two. The experimental results obtained throughout these investigations bear out the theory, and constitute a most elegant means for a detailed investigation of the interaction of matter with the electromagnetic radiation field.

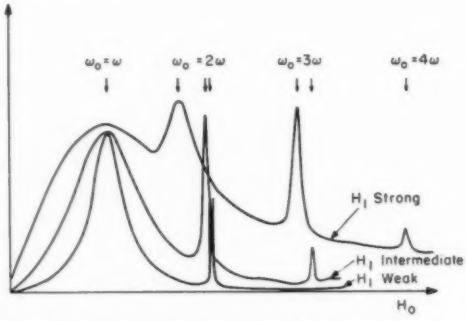

Fig. 10. Multiple quantum transitions found between the Zeeman levels of the ground state of sodium.

A final aspect of transitions between atomic-energy levels, which we discuss here, is the role of collisions. These we divide into two classes. First, those that produce or destroy atomic orientation, and second, those that excite or de-excite electronic levels.

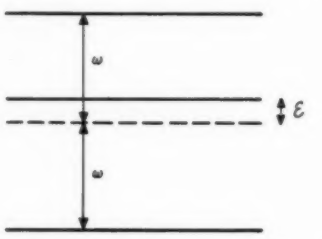

Fig. 11. Intermediate levels in multiple quantum transitions.

The question of selective excitation of Zeeman or hyperfine components by oriented beams of electrons having closely controlled energies has already been discussed as an important modification of the double-resonance technique, which is enormously important for the investigation of levels other than resonance levels. The subject appears to be of interest primarily because of its practical usefulness in this connection.

The disorienting effect of collisions with solid-container walls or with atoms is a quite different matter. On the one hand, extensive investigations have been carried out on optically oriented alkali vapors in their paramagnetic ground state.[47,48] Collisions between alkali atoms and glass walls appear to produce reorientation more or less on every collision, but various coatings appear to be effective in preventing this. Thus, for example, Robinson *et al.*[49] and Franzen[50] report organic coatings that greatly reduce this effect.

The most severe source of disorientation under certain circumstances, however, is the occurrence of electron exchange between like atoms during collisions. The cross section for this has been estimated[50] as approaching 1000 times the kinetic theory cross section. Collisions with diamagnetic rare gas atoms, on the other hand, have little effect on the orientation, the cross sections in oriented Rb vapor being estimated in the range 10^{-7}–10^{-4} of the kinetic theory cross section in the series Ne, A, Kr, Xe.

During the last few years, extensive work has been done on diamagnetic Hg atoms with odd-A nuclei. This work has recently been reviewed by Cagnac.[51] There are distinctively different results for the two stable isotopes, Hg^{201} with a nuclear spin of $^3/_2$, and Hg^{199} with a nuclear spin of $^1/_2$. The former has a nuclear quadrupole moment. In a collision, the nucleus may be exposed to an electric-field gradient, for example, because of the deformation of the atom, and this exerts a torque that is instrumental in producing reorientation. There is no such nuclear quadrupole moment in Hg^{199} and its nuclear orientation is consequently much more stable. The nuclear orientation in a vapor containing this isotope can have a much longer lifetime, and the nuclear magnetic-resonance curves can be much narrower. The actual mechanism (or mechanisms) responsible for producing thermal equilibrium is not clear, at present, and the observed relaxation effects and line widths require further experimental investigation. One of the very interesting results of this work is that it is apparently possible to study not only the various collision processes involved, but the actual duration of contact of a mercury atom with a wall. In the investigations reported with fused quartz cells used, this was estimated to be at least 1000 times the duration of an elastic collision at room temperature, but was markedly decreased by heating the cell.

Of great interest in another context are collisions leading to excited states. The great interest in plasmas indicates their practical and theoretical importance, and it is clear that in order to use them effectively and understand their properties thoroughly we shall have to investigate them in the same detail, for example, to which solid-state semiconductors have been examined on a world-wide scale during the past decade. In addition to studies of the electron-energy distribution and concentration, the ambipolar diffusion to the walls, and the extent of volume recombination of ions and electrons, we must also know something of the transitions between the various excited states and the radiations leaving the plasma. Figure 12, taken from an article by Kenty,[52] illustrates the complexities, even in a simplified energy-level diagram. Direct experimental evidence for the correctness of the calculations is greatly to be desired and could be supplied by accurate measurement of the various level widths, as has been done, for example, for the $^3P_1$ level in a resonance lamp. Such measurements have not yet been attempted, but would be most valuable to the student of plasma physics. A technique that may prove of importance in this connection is to measure the magnetic-resonance line width in a small-resonance lamp adjacent to the discharge that is to be investigated. The resonance lamp will, after all, be coupled to the discharge in just the same way as atoms in the same resonance cell, as studied by Barrat and others, are coupled to each other. The effects going on in the discharge can then be monitored externally more conveniently.

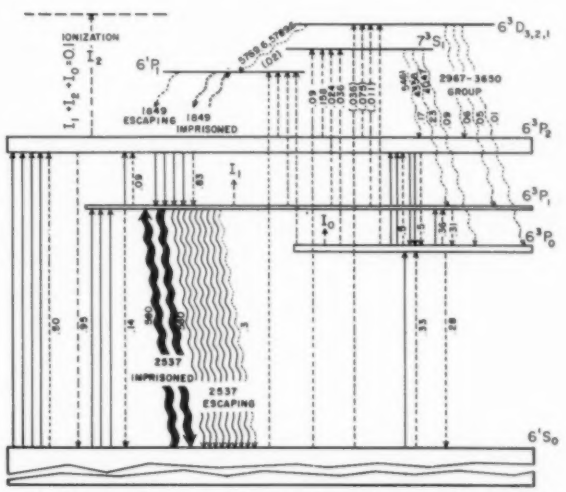

Fig. 12. A diagram after Kenty,[52] showing the principal processes occurring in a fluorescent lamp plasma-mercury vapor plus a few mm of rare gas, usually argon. Straight arrows are calculated collisions of the first and second kinds. Wavy arrows are measured radiation outputs (except for the heavy arrows). One full arrow, either straight or wavy, represents 3×10^{18} transitions per second per centimeter of length. Decimals are fractions of full arrows.

This is, perhaps, a good note on which to end this review. There is much fascinating work to be done in many fields with these new experimental techniques. There is still ample room for originality.

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Composite Rod Optical Masers

G. E. Devlin, J. McKenna, A. D. May, and A. L. Schawlow

A new optical maser structure is described which reduces the threshold pumping power and increases the available output. It consists of a composite rod, which has a core of maser material (e.g., ruby) covered by a coaxial sheath of transparent refractive material (e.g., sapphire). Refraction of pumping light by the sheath is shown to increase the intensity at the active core. The structure also facilitates cooling by providing an increased surface area.

I. Introduction

Most solid optical masers described so far have had structures similar to that proposed by Schawlow and Townes.[1,2] This is, essentially, a rod of the active material whose ends are polished plane and parallel, and coated to reflect light. The sides are left clear to admit pumping light; they may be either polished or roughly ground. The pumping light from a powerful lamp or lamps enters through the side walls, and excites some ions in the crystalline rod. Then light of an appropriate wavelength (always longer than that of the pumping light) can stimulate the excited atoms to emit. Light of this output wavelength traveling along the axis of the rod is amplified by stimulated emission. On being reflected from the ends, it continues to grow, and a coherent wave is established in the rod. Some of this light is allowed to escape through a partially transmitting end surface, and produces a very intense collimated beam with relatively narrow wavelength spread.

If we neglect scattering by inhomogeneities in the rod material, the threshold requirement for optical maser oscillation can be expressed simply as a requirement that the amplification by stimulated emission be sufficient to make up for the transmission and absorption losses at the ends.[3] This determines the number of ions which, at any instant, must be maintained in the excited state. Since excited atoms decay by spontaneous emission or other processes in a rather short time, they must be supplied very rapidly. This means that to maintain the threshold number of excited atoms, new excited atoms must be supplied at a certain minimum rate.

The number of excited atoms which must be supplied per second is [1,3] (for a Gaussian line shape)

$$\frac{8\pi^2}{(\pi \ln 2)^{1/2}} \cdot \frac{1}{\varphi t} \cdot \frac{V}{\lambda^3} \cdot \frac{\Delta\nu}{\nu} \qquad (1)$$

where

φ = fraction of atoms which decay by any way other than in the desired transition
t = lifetime of light in the resonator
V = volume of the resonator
λ = wavelength of the emitted light in the material
ν = frequency of the emitted light
$\Delta\nu$ = width of the line emitted in spontaneous emission.

Since the number required is proportional to the volume, one needs a high density of excited atoms. More strictly, since t is proportional to the length, the pumping power is proportional to the cross sectional area.

Each excited atom requires the absorption of at least one quantum of pumping radiation. Thus there is a threshold rate at which suitable pumping radiation must be supplied and absorbed. This rate is typically of the order of 1 to 1000 watts/cm^2. Very bright lamps are needed to supply such a high light intensity. Moreover, as the output quanta are necessarily smaller than the input quanta some heat must be dissipated in the crystal, and usually a substantial fraction of the pumping power appears as heat. Because of these two requirements, continuous operation has not yet been achieved for any solid optical maser.

We wish to describe here a structure for the optical maser rod which reduces the required intensity of pump-

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ing light. At the same time, the new structure is more readily cooled than is the simple rod. It takes advantage of the fact that the solid material, of which the rod is composed, necessarily has a refractive index greater than unity.

When rays of pumping light strike the side surface of a dielectric cylinder, as in Fig. 1, they are refracted toward the normal. Even for incident rays with an angle of incidence as large as 90°, the angle of refraction is $\theta_{max} = \sin^{-1}(1/n)$, where n is the index of refraction.

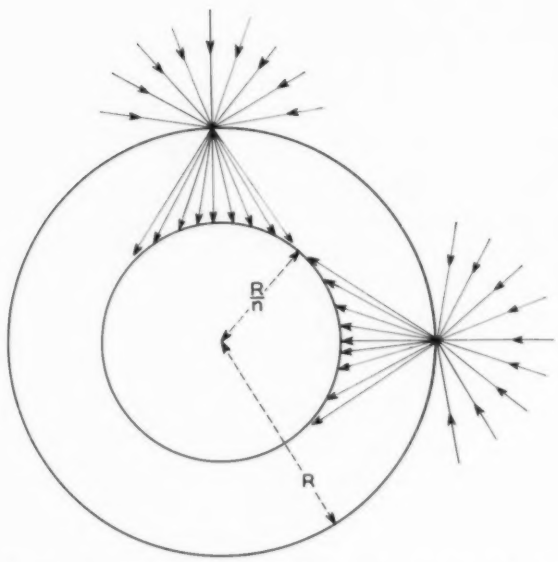

Fig. 1. Rays of light incident on the side wall of a dielectric cylinder are refracted toward the axis.

For sapphire, which is a base material commonly used for optical masers,[4,5,6] $n = 1.76$, so that $\theta_{max} = 35°$. Such a ray passes the axis of the cylinder with a minimum distance $r = R/n$, where R is the radius of the cylinder. Thus, all the light which falls at a point on the surface of the cylinder passes within a cone of 35° half angle, and approaches the axis of the cylinder to a distance not greater than R/n. That is, all the light that penetrates the surface of the cylinder of radius R eventually passes through a smaller internal cylinder of radius R/n.

We can take advantage of this concentration of light at the center of the rod by making a composite rod as in Fig. 2. The central portion of the rod is doped with the required transition of rare earth metal ions, while the outer region contains merely the base material. For example, the rod might be constructed of sapphire (Al_2O_3), with chromium ions added to the central region only. Such a composite rod may be made by first preparing a core rod of single crystal ruby, and then using this as a seed onto which sapphire is deposited.

With a composite rod of this sort, the light intensity at the ruby core is greater than without the sapphire sheath. Conversely, for a given radiant flux intensity at the core, the brightness of the pumping lamp can be less.

There is another way of looking at the operation of the composite rod. When viewed from a point outside, the ruby core appears to have a larger diameter when it is enclosed by the sapphire sheath. Thus, at a point on the pumping lamp the sapphire sheath causes the ruby rod to subtend a larger angle, and so to receive a larger fraction of the emitted light. Since this is true for every point on the lamp, the ruby rod receives more light from the lamp than in the absence of the transparent sheath.

Removal of this heat is facilitated by the composite rod structure. The sort of hard crystals suitable for optical masers are very good conductors of heat, especially at low temperatures. For instance, the thermal conductivity of sapphire[7] reaches a peak of around 60 watts/cm °K near 40°K. The worst barrier to heat flow is at the surface of the crystal. The surface area of the composite rod is considerably larger than for the core alone. Thus heat transfer to a cooling medium is facilitated.

II. Calculation of the Energy Density Inside a Dielectric Cylinder

In this section of the paper we use geometrical optics to analyze an idealized model, which we feel gives a reasonably good qualitative description of the optics involved in the actual case.

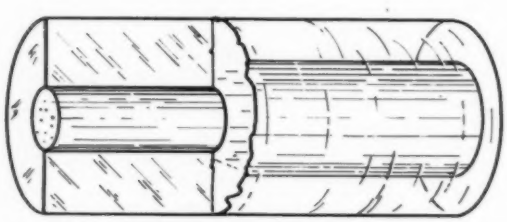

Fig. 2. Composite rod structure. The core section is doped, as for ruby, while the outer sheath is clear (e.g., sapphire).

Consider two concentric, circular, dielectric cylinders of infinite length (Fig. 2). Let the radius of the inner cylinder, or core, be R_1, and the radius of the outer cylinder, or sheath, be R_0. The indices of refraction of both the core and the sheath are the same and are equal to n, which is a good description of the actual situation. The sheath is lossless, but the core is absorptive. We describe the absorption in the core by an attenuation constant η. That is, in traversing a length dx of the core material, the intensity of a beam of light, I, is decreased by an amount $dI = -2\eta I dx$. This, of course, is equivalent to saying that in traversing a distance x in the core, the intensity of a beam of light will be attenuated by a factor $e^{-2\eta x}$.

The light incident on the cylinder is assumed to be a superposition of incoherent plane waves. The propagation vectors of these plane waves all lie in a plane perpendicular to the axis of the cylinder, and in this plane the distribution in direction of the propagation vectors is uniform and continuous. The energy density of each incident plane wave is infinitesimal and the same for each wave. The time average energy density, du_0, at a point in free space due to all those incident plane waves whose propagation vectors lie inside the element of angle $d\alpha$ is $du_0 = {}^1/_2\epsilon_0 E_0^2 d\alpha$, where ϵ_0 is the permittivity of free space, and E_0 is a constant proportional to the maximum amplitude of the electric vector in each incident plane wave. We are explicitly making use at this point of the assumption of incoherence, because we have added the intensities of the superposed waves. As a consequence, the total energy density at a point in free space is

$$u_0 = \int_0^{2\pi} {}^1/_2\,\epsilon_0 E_0^2 d\alpha = 2\pi \cdot {}^1/_2\,\epsilon_0 E_0^2. \tag{2}$$

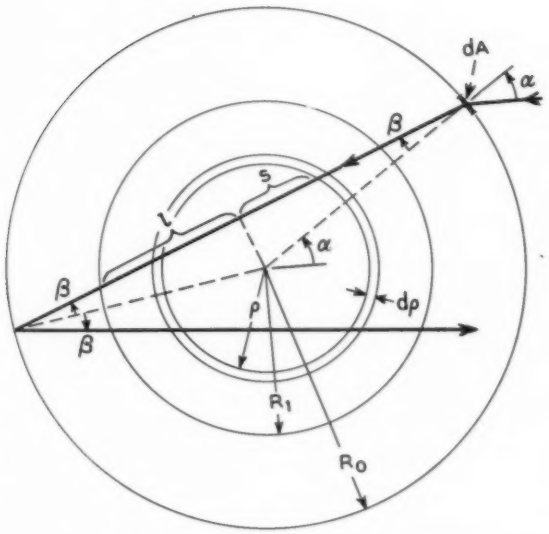

Fig. 3. Path of rays inside a dielectric cylinder.

We assume that the incident waves are all plane polarized with their electric vectors parallel to the axis of the cylinder. If it is assumed that the magnetic vector of each wave is parallel to the axis of the cylinder, the formulas which result differ little from those we shall derive, and so for the sake of brevity we do not consider them here. In the limiting case of zero absorption the expressions for the energy density are the same for both polarizations. Since the radii of both the core and the sheath are very large compared to the wavelength of the light, we use the approximation of geometrical optics. The final assumption is that all interference effects are neglected.

Now consider a single wave incident on the cylinder. We propose to calculate the rate at which the energy of this wave is dissipated in a ring of radius ρ, infinitesimal thickness $d\rho$, and unit length ν (cf. Fig. 3). Let $dA = \nu R_0 d\alpha$ be an element of area on the surface of the sheath, where the radius from the center of the core to dA makes an angle α with the direction of propagation of the incident wave, as shown in Fig. 3. The portion of the incident wave which falls on dA has an angle of incidence α, and the transmitted portion of this beam has an angle of refraction β, which is related to the angle of incidence by Snell's law,

$$n \sin\beta = \sin\alpha. \tag{3}$$

The time average power incident on dA is $dA \cos\alpha\, S_0$ and the time average power transmitted through dA is[9]

$$nt^2 dA \cos\beta\, S_0, \tag{4}$$

where

$$S_0 = \frac{1}{2}\sqrt{\frac{\epsilon_0}{\mu_0}}\, E_0^2, \tag{5}$$

μ_0 is the magnetic permeability of free space, and t is the transmission coefficient,[9]

$$t = \frac{2\cos\alpha}{\cos\alpha + n\cos\beta}. \tag{6}$$

If we now trace the path of this transmitted beam as it is successively reflected internally, we see that at each internal reflection at the outer surface of the sheath, the internal angles of incidence and reflection are β, and the power of the beam is diminished by a factor r^2, where r is the reflection coefficient,[9]

$$r = \frac{n\cos\beta - \cos\alpha}{n\cos\beta + \cos\alpha}. \tag{7}$$

If $2l$ is the total distance the beam travels in a single passage through the core, the power of the beam is diminished by a factor $e^{-4\eta l}$ in each traversal. From simple geometrical reasoning, we see that

$$l = \sqrt{R_1^2 - R_0^2 \sin^2\beta}. \tag{8}$$

Similarly, in reaching the ring of radius ρ, the beam must travel a distance $l + s$ or $l - s$ through the core, depending on the direction from which it approaches the ring, and the power of the beam is consequently reduced by a factor $e^{-2\eta(l \pm s)}$, where

$$s = \sqrt{\rho^2 - R_0^2 \sin^2\beta}. \tag{9}$$

Finally, each time the beam passes through the small ring of radius ρ and thickness $d\rho$, the power dissipated is $2\eta ds$ times the power in the beam at that time, where from (9)

$$ds = \frac{\rho d\rho}{s}. \tag{10}$$

Thus the total power dissipated in the ring by this beam is

$$dP = (nt^2 dA \cos\beta\, S_0)\left(2\eta \frac{\rho d\rho}{s}\right)(e^{-2\eta(l+s)} + e^{-2\eta(l-s)}) \cdot \sum_{p=0}^{\infty} (r^2 e^{-4\eta l})^p. \tag{11}$$

The geometrical series in (10) can be readily summed, and yields

$$\sum_{p=0}^{\infty} (r^2 e^{-4\eta l})^p = \frac{1}{1 - r^2 e^{-4\eta l}}. \tag{12}$$

The power, P, dissipated in the ring by this single wave is obtained by integrating over all the surface area of the sheath from which a beam can reach the ring of radius ρ. Thus

$$P = (\nu R_0 n S_0)(2\eta\rho d\rho) \cdot \int_{-\alpha_0}^{\alpha_0} \frac{t^2 \cos\beta (e^{-2\eta(l+s)} + e^{-2\eta(l-s)}) d\alpha}{(1 - r^2 e^{-4\eta l}) s}, \tag{13}$$

where

$$\sin\alpha_0 = \min\left\{1,\ n \frac{\rho}{R_0}\right\}. \tag{14}$$

From our original assumption about the isotropy of the incident field, we see that the total power dissipated in the ring is $2\pi P$, and the power must be dissipated uniformly throughout the ring. Thus at a distance ρ from the center of the core, the power dissipated per unit volume is

$$-\frac{du}{dt} = \frac{2\pi P}{\nu 2\pi\rho\, d\rho}, \tag{15}$$

where u is the energy density. Making use of our assumption about the attenuation in the core, we see that

$$\frac{du}{dt} = \frac{du}{dx}\frac{dx}{dt} = \frac{c}{n}\frac{du}{dx} = -2\eta \frac{c}{n} u, \tag{16}$$

where c is the velocity of light in vacuo. Therefore

$$u = \frac{nP}{2c\eta\nu\rho d\rho}. \tag{17}$$

If we make use of the relationship

$$\frac{1}{c} S_0 = \frac{1}{2} \epsilon_0 E_0^2 = \frac{1}{2\pi} u_0, \tag{18}$$

and Eqs. (6), (7), (13), and (17), we can deduce that

$$\frac{u}{u_0} = \frac{4n^2 R_0}{\pi} \cdot \int_0^{\alpha_0} \frac{\cos^2\alpha \cos\beta \cosh 2\eta s\, d\alpha}{s[(\cos^2\alpha + n^2\cos^2\beta)\sinh 2\eta l + 2n\cos\alpha\cos\beta\cosh 2\eta l]} \tag{19}$$

where α_0 is given by (14), l is given by (8), s is given by (9), and β is related to α by Snell's law (3). Equation (19) is the desired equation, giving, as a function of ρ, the ratio of the energy density in the core to the energy density in free space. The dependence on ρ lies in α_0 and s.

To obtain an idea of the shape of the curve of the energy density ratio as a function of the distance ρ from the center for the case where η is small (the case of interest), consider the limiting case when the attenuation vanishes, $\eta = 0$. Then

$$\frac{u}{u_0} = \frac{2nR_0}{\pi}\int_0^{\alpha_0} \frac{\cos\alpha\, d\alpha}{\sqrt{\rho^2 - (R_0/n)^2 \sin^2\alpha}} = \begin{cases} n^2, & 0 \le \rho \le R_0/n \\ (2n^2/\pi)\sin^{-1}(R_0/n\rho), & R_0/n \le \rho \le R_0. \end{cases} \tag{20}$$

The form of this function suggests that for small η, the optimum value of the ratio R_1/R_0 is $1/n$. The graph of u/u_0 as a function of ρ/R_0, where $n = 1.76$ (as for sapphire) and $\eta = 0$, is given in Fig. 4. It is seen that the intensity in the central region ($\rho \le R_0/n$) is indeed greater than the average for the whole rod.

In concluding this section, it should be remarked that the model used here is energetically self-consistent. By this we mean that it can be shown that the total rate at which energy is incident on the sheath is equal to the rate at which energy is absorbed in the core plus the rate at which energy is both reflected from the sheath and transmitted through the system.

III. Experimental Tests

As a preliminary test of the general correctness of these ideas, the rod was simulated by a large graduated cylinder, which was filled with liquids of various indexes of refraction from 1.3 to 1.65. The cylinder was placed inside a white box designed to provide nearly uniform illumination from all directions. Light intensity inside the cylinder was probed with a small photovoltaic cell.

As expected, the intensity at the axis of the cylinder was higher than near the surface. The rise was greater and occurred closer to the surface when the liquid of high refractive index was used.

Composite rods of single crystal sapphire with a core of 2 mm diameter containing about 0.05% of

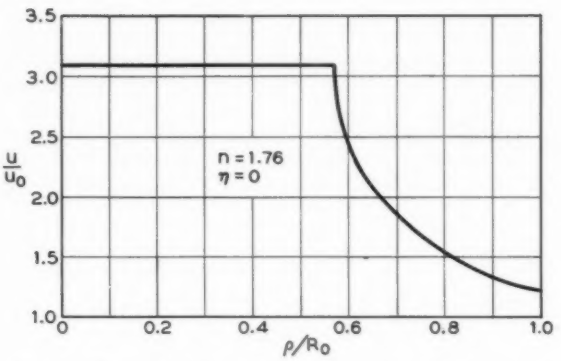

Fig. 4. Energy density of light, as a function of radius, inside a dielectric cylinder illuminated by rays from all directions in a plane perpendicular to the cylinder axis.

Cr_2O_3, and an over-all diameter of 5 mm, were prepared by the Linde Co. For two of the four rods, the crystal *c*-axis was oriented along the rod axis, for the other two it was perpendicular to the rod axis. These crystals were relatively unstrained, as shown by the narrow width (0.010 cm^{-1}) of the fluorescence line at 20°K.[8] The ends of the rods were polished flat and parallel by Laboratory Optical Co., Green Brook, New Jersey, and were silver coated.

Ideally, one would wish to determine the thresholds of the same ruby core for maser action with and without the clear sapphire sheath. Since addition or removal of the sheath involves rather drastic treatment of the rod, this is not possible. Instead, the threshold was determined for each of the four rods, and compared with that required for good ruby rods of similar size and chromium concentration. Each rod was placed, in turn, inside a large spiral flash lamp (General Electric type FT 524), and the threshold energy for maser action was determined. The values obtained depend on the particular lamp and geometry used, but this is the same for all samples. The comparisons were made at low temperature (<100°K) where the threshold is less sensitive to strains and imperfections than at room temperature. Qualitatively similar results were obtained at room temperature.

The composite rods had threshold energies for optical maser action which ranged from 460 to 490 joules (80 μf, 3400–3500 volts). No significant variation with crystal orientation was noted. With the same capacitor, the solid ruby rods required 750 joules or more for maser action.

In all cases, the threshold energies for the composite rods were observed to be appreciably lower than for the solid rods. The energies required, for all these good ruby rods, are very low for this geometry. Much lower thresholds for all the rods can be obtained with a straight lamp and rod at the two foci of an elliptic cylinder.[10] One of the composite rods was tested in the elliptic cylinder of a small portable optical maser built by J. W. Ammons, and had a threshold energy of 78 joules at room temperature. Although the apparatus was not well suited to cooling, a threshold of 64 joules was attained at a somewhat reduced temperature. An improved elliptic cylinder, with better provision for cooling, permitted maser action at 44 joules per flash at 77°K.

IV. Conclusions

It has been demonstrated theoretically and experimentally that the transparent sheath of the composite rod structure reduces the threshold pumping energy necessary for maser action. The discussion has been mostly in terms of ruby with a sapphire sheath, but the same principles apply to any solid optical maser material.

As a direct consequence of the reaction in threshold energy, the output power must be higher at any given pumping level. Moreover, if reflection from side walls interferes with mode selection, the composite rod alleviates the problem by moving the side walls away from the active medium. Incidentally, only the ends of the core need to be polished flat and coated with reflecting material for maser action.

The structure also provides a larger surface area for dissipating heat, although no experimental investigation of heat transfer has been made. Composite rods can be made by encapsulating a rod of maser material in, for example, plastic, but the cooling advantage is lost.

It is worth noting that if it is necessary to sheath the pumping lamp (as for cooling), the lamp is magnified and its surface brightness is reduced. These undesirable effects should be minimized by keeping the lamp sheath small, and of low refractive index.

The authors wish to thank Dr. S. P. Morgan for much valuable advice and in particular for outlining the derivation of the energy density given in Section II.

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New Companies. . . . **Jason L. Saunderson** has become president of a new company, Research and Control Instruments, Inc., of Woburn, Mass. This company plans to develop, manufacture, and sell analytical instruments operating on the basis of optical emission systems, atomic absorption, and vapor phase chromatography . . . . **George Aroyan and Theodore R. Whitney,** formerly of Space Technology Laboratories, have formed a new company, Pacific Infrared, in Woodland Hills, Calif. . . . The **Optic-Electronic Corporation,** which offers services in optical and electronic research, design, development and manufacture, began operation at 2605 Manana Drive in Dallas, Tex., in October 1961.

As part of its Employee Development Program, the **National Bureau of Standards** currently has 14 selected staff members pursuing full-time training of 6 to 12 months to increase their capabilities for carrying out future NBS assignments. The scientists selected carry out individual research programs under the supervision of outstanding leaders in their respective fields. In the field of optics, **Isadore Nimeroff** of the Photometry and Colorimetry Section is presently working with W. D. Wright, of the Technical Optics Section, Imperial College of Science and Technology, London . . . . A cavity resonator has been developed at the NBS Boulder (Col.) Laboratories for the study of millimeter radio waves. By using the Fabry-Perot interferometer as part of a resonator, the length of millimeter waves may be measured with great accuracy. Properties of materials, such as the dielectric constant of plastics, may also be studied with this device . . . . As part of its program to insure accurate and uniform measurements, the NBS calibrates optical pyrometers for science and industry. These calibrations are performed over the temperature range of 800–4200°C; the uncertainty of the calibration varies from about 3 deg (at 1063°C) to 40 deg (at 4200°C).

The name of the American Society for Testing Materials was officially changed to the **American Society for Testing AND Materials** on 18 September 1961. The two largest electrical and radio societies, the **American Institute of Electrical Engineers** and the **Institute of Radio Engineers** with 150,000 members, are exploring the feasibility of consolidating to form a new *international* engineering body.

Drive to improve high school teaching. A grass roots attack to improve the quality of high school physics teaching has been launched jointly by the *American Association of Physics Teachers* and the *American Institute of Physics* by the creation of a Regional Counselor Program in Physics. College professors and physicists in industry and government, who are interested in promoting local cooperation for better physics teaching, have been appointed in 40 states and Puerto Rico. By the end of the present academic year it is expected that 50 counselors will be working to achieve the goals of the Program, and next year this number will be doubled by the addition of more counselors in the larger and more populous states. **Is There a Future Scientist or Engineer in your Home?** is the title of a booklet just released by Battelle Memorial Institute. The booklet outlines characteristics which *may* indicate an embryo engineer or scientist and emphasizes that, if not discovered early enough, the student may find it difficult to succeed at the university. Where to seek specific counsel and the possibilities of financial aid are also dealt with. Single copies are available *free* from the Public Services Office, Battelle Memorial Institute, Columbus 1, Ohio.

A report by the British Advisory Council on Scientific Policy's Statistics Committee—*The Long-Term Demand for Scientific Manpower*—somewhat startlingly appears to indicate that, in 4 years' time, Britain's supply of scientists and technologists "will be broadly in balance with demand," while in ten years' time, it is suggested that there is a likelihood of a substantial surplus of qualified manpower. However, in an accompanying memorandum, the Committee on Scientific Manpower emphasizes that a shortage of scientific manpower "will continue for a long time in the educational field." It cannot be denied that the scientifically-trained mind has much potential value in other than strictly scientific areas, and the British Committee warns against "the risk of significantly underestimating the demand" especially when sudden technological developments cannot be foreseen ten years ahead.

The *New York Times* reports that Eastman Kodak finds a pinch of sugar will improve the developer used in processing x-ray film.

CORPORATION MEMBERS OF THE OPTICAL SOCIETY OF AMERICA

AEROJET-GENERAL CORPORATION, Azusa, California, *carries on optical research and development at the Astronics Division. Approximately 850 engineering and supporting personnel are engaged in the various aspects of research and development of infrared and optical instrumentation for scientific and military applications. Prime fields of interest are surveillance, tracking, fire control, and measurements in airborne and space environments. Facilities are provided for design, fabrication, laboratory studies, and manufacturing.*

AERONUTRONIC DIVISION, FORD MOTOR COMPANY, Newport Beach, California, *is geared to help meet the defense and related commercial needs of the United States. Aeronutronic is a part of Ford's Defense Products Group, which also consists of the Special Military Vehicles Operations in Dearborn, Michigan. The Newport Beach firm is engaged in development and manufacture of tactical weapons, space systems, strategic systems, and electronics.*

AEROSPACE CORPORATION, El Segundo, California, *is a nonprofit, public service institution and does not engage in production or manufacture of hardware. It was formed in June 1960 to provide an organization of high technical competence to assist the Air Force in the scientific-engineering planning and direction of missile-space programs. The Corporation engages in forward planning in connection with advanced ballistic missile and space systems.*

AMERICAN CYSTOSCOPE MAKERS, INC., Pelham Manor, New York, *has been engaged in the design, development, and manufacture of optical and electronic, diagnostic and operative medical equipment since 1900. It has been engaged in the development of fiber optics for the past eleven years and has been active in the manufacture of fire control systems, telescopes, periscopes, range finders, bombsights, and other military and industrial inspection equipment such as borescopes and alignment telescopes.*

AMERICAN OPTICAL COMPANY, Southbridge, Massachusetts, *founded in 1833, manufactures ophthalmic products. More than 2000 different products are made by AO, ranging from the tiny screws used in fashionable eyewear to space helmets and missile trackers. It also manufactures safety products, sun glasses, and scientific instruments, including microscopes and telescopes. The research center is devoted to the application of basic science to improving man's perception of his environment.*

ANSCO DIVISION, GENERAL ANILINE AND FILM CORPORATION, Binghamton, New York.

APPLIED PHYSICS CORPORATION, 2724 South Peck Road, Monrovia, Calif.

BAIRD-ATOMIC, INC., 33 University Road, Cambridge, Massachusetts, *is currently celebrating its 25th anniversary, being founded for consulting and instrument development in the area of applied physics. Incorporated as Baird-Associates in 1947, the Cambridge, Massachusetts, firm merged with the Atomic Instrument Company in 1956. Today, Baird-Atomic, Inc., derives its business from commercial sales of atomic, spectrochemical and electronic instruments in addition to research, development, and engineering contracts for various U.S. government agencies.*

BARNES ENGINEERING COMPANY, Stamford, Connecticut, *is engaged in the fields of infrared and electro-optics, in which its activities include research, design, development and manufacture of components, instruments, and systems. It specializes in the production of infrared detectors, radiation sources, instruments for the measurement and analysis of infrared radiation, and thermal scanning cameras. The Company has pioneered in the development of missile and space vehicle instrumentation including trackers, horizon sensors, and meteorological radiometers; Barnes equipment is currently being employed in such important programs as Polaris, Tiros, Nimbus, and Project Mercury.*

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Atomes à l'Intérieur d'un Interféromètre Perot-Fabry

A. Kastler

In the optical masers realized so far a Perot-Fabry device is used as a multimode cavity. It may be interesting to investigate the general properties of such a device when the emitting or the absorbing atoms are put inside the reflecting mirrors. Even in the case when this device works below the threshold of maser action it shows remarkable properties which are worthwhile studying experimentally. The following aspects are considered in the paper: In the case of external illumination, the distribution of light intensity inside a Perot-Fabry interferometer is calculated. It is shown that the local light intensity in the stationary waves inside can be much higher than the intensity of the incident light beam. The properties of light emitted by atoms inside the Perot-Fabry and emerging from it are investigated. Narrow fringes of very strong intensity can be obtained. If the emitting atoms are located in an atomic beam the central fringe has natural line width, the Doppler broadening being suppressed. The realization of a fluorescent medium of lamellar structure is discussed. This structure favors one special mode of emission fringes. Finally, the absorption of atoms inside the interferometer is studied. It is shown that this device is equivalent to a long absorption path in an ordinary light beam.

I. Rappel des Propriétés Extérieures de l'Interféromètre Perot-Fabry

Dans leur mémoire sur les Masers Optiques, Schawlow et Townes[1] ont suggéré d'utiliser un interféromètre Perot-Fabry (P.F.) comme une cavité multimode. Ce mémoire a l'intérêt d'attirer l'attention sur le comportement des atomes à l'intérieur d'un tel interféromètre.

Nous nous proposons de montrer qu'en absence de toute production d'émission induite, lorsque les atomes absorbent ou émettent la lumière sans relation de cohérence les uns avec les autres, un tel système présente des propriétés intéressantes et qui méritent d'être exploitées.

Commençons par rappeler les propriétés classiques du P.F., ses "propriétés extérieures."[2,3] L'appareil est constitué par deux plans semi-réfléchissants parallèles possédant des pouvoirs réflecteurs R supposés identiques et voisins de l'unité, des coefficients de transmission T. Lorsque les couches réfléchissantes sont diélectriques, il n'y a pas de pertes d'absorption. La relation $R + T = 1$ se trouve alors satisfaite. Les couches diélectriques actuellement employées atteignent des pouvoirs réflecteurs $R = 0.94$.[4] Les coefficients R et T interviennent comme facteurs multiplicatifs des intensités lumineuses. Il leur correspond comme facteurs multiplicatifs des amplitudes les coefficients $r = \sqrt{R}$ et $t = \sqrt{T}$.

Dans l'exemple précédent $R = 0.94$, $T = 1 - R = 0.06$ et $r = 0.97$, $1 - r = 0.03$.

Lorsqu'on éclaire le P.F. avec une onde plane monochromatique d'incidence i on obtient par transmission une suite d'ondes planes présentant des différences de phases φ en progression arithmétique

$$\varphi = (2\pi/\lambda)\, 2ne \cos i$$

et des amplitudes en progression géométrique décroissante: $t^2, t^2r^2, t^2r^4, \ldots t^2r^{2n}$ (nous posons égale à l'unité l'amplitude de l'onde incidente).

L'intensité émergente présente une variation angulaire suivant la *fonction d'Airy:*

$$I = I_0\, Ay\,(i)$$

$$I_0 = \left(\frac{t^2}{1 - r^2}\right)^2 = \frac{T^2}{(1 - R)^2}$$

$$Ay(i) = \frac{1}{1 + m \sin^2\varphi/2} \qquad m = \frac{4R}{(1 - R)^2}.$$

La finesse des anneaux est caractérisée par le rapport f de la largeur à mi-hauteur des franges brillantes ($\delta\varphi/2 = 2/\sqrt{m}$) à l'intervalle des franges ($\Delta\varphi/2 = \pi$):

$$f = \frac{\delta\varphi}{\Delta\varphi} = \frac{2}{\pi\sqrt{m}} = \frac{1 - R}{\pi\sqrt{R}} \approx \frac{1 - r^2}{\pi r}.$$

Pour des couches diélectriques $t^2 = 1 - r^2$, l'intensité des maxima I_0 est égale à l'unité, c'est-à-dire égale à l'intensité du faisceau lumineux incident. Pour les angles d'incidence qui correspondent à l'accord de phase ($2ne \cos i = k\lambda$) l'interféromètre joue le rôle d'une couche antiréfléchissante.

Toutes ces propriétés sont bien connues et utilisées avec succès pour l'analyse des structures fines et hyperfines des raies spectrales.

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II. Intensité Lumineuse à l'Intérieur d'un P.F.

Considérons maintenant, dans les mêmes conditions d'éclairement, un point M à l'intérieur des deux plans réfléchissants (Fig. 1). Soit z sa cote verticale. En M se rencontrent un ensemble de rayons qu'on peut grouper en deux suites d'Airy distinctes:

(a) une suite provenant des rayons incidents a_1, a_2, a_3, etc. (indiqués en trait plein) qui en M possèdent les amplitudes: t, tr^2, tr^4, etc., et qui donnent lieu en M à une vibration résultante d'amplitude

$$a = \frac{t}{1 - r^2} [Ay(i)]^{1/2}.$$

(b) une suite provenant des rayons incidents b_1, b_2, b_3, etc. (indiqués en trait interrompu) qui en M possèdent les amplitudes: tr, tr^3, tr^5, etc. et qui donnent lieu en M à une vibration résultante d'amplitude

$$b = \frac{tr}{1 - r^2} [Ay(i)]^{1/2}.$$

Les vibrations de ces deux systèmes présentent l'une par rapport à l'autre une différence de phase

$$\psi = \frac{2\pi}{\lambda} \cdot 2nz\cos i + C^{te}.*$$

La vibration résultant de la composition des deux résultantes partielles a pour intensité:†

$$I = (a - b)^2 + 4ab \cos^2 \frac{\psi}{2}$$

$$I = I_{\min} + I_{\max} \cos^2 \frac{\psi}{2}$$

$$I_{\max} = 4ab = \frac{4t^2 r}{(1 - r^2)^2} Ay(i) = \frac{4T\sqrt{R}}{(1 - R)^2} Ay(i) = \frac{4\sqrt{R}}{1 - R} Ay(i)$$

$$I_{\min} = (a - b)^2 = \left[\frac{t(1 - r)}{1 - r^2}\right]^2 Ay(i)$$

$$= \left(\frac{t}{1 + r}\right)^2 Ay(i) = \frac{1 - r}{1 + r} Ay(i).$$

Le rapport

$$\frac{I_{\min}}{I_{\max}} = \frac{(1 - r)^2}{4r}.$$

Pour le cas de notre exemple numérique $I_{\min}/I_{\max} \approx 2 \times 10^{-4}$. Négligeant $I_{\min}$, nous pouvons poser:

$$I = I_{\max} \cos^2 \frac{\psi}{2} = \frac{4\sqrt{R}}{1 - R} \cdot \frac{1}{1 + m \sin^2 \varphi/2} \cdot \cos^2 \frac{\psi}{2}.$$

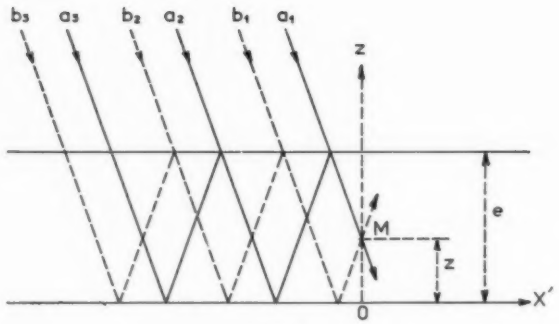

Fig. 1

φ ne dépend que de la variable i; ψ dépend de i et de z.

Pour une onde plane incidente d'inclinaison i donnée

$$I = I_{\max} \cos^2 \left(\frac{\pi}{\lambda} \cdot 2nz \cos i\right).$$

L'intervalle entre les plans réfléchissants est divisé en franges d'épaisseur $\Delta z = \lambda/2n \cos i$, la répartition d'intensité y étant sinusoidale en fonction de z.

Lorsque l'inclinaison i correspond à l'accord de phase ($2ne \cos i = k\lambda$ et $Ay(i) = 1$), l'intensité maximum de ces franges est:

$$I_1 = \frac{4\sqrt{R}}{1 - R} = \frac{40.97}{0.06} \approx 64.$$

Il existe donc à l'intérieur du P.F. des zones où l'intensité lumineuse est beaucoup plus grande que dans l'onde incidente. Si, au lieu de considérer le facteur d'amplification local dans les plan des maxima $\cos^2\psi/2 = 1$, nous considérons le facteur d'amplification global, il nous faut multiplier par $\overline{\cos^2\psi/2} = 1/2$. Nous trouvons pour l'intensité moyenne:

$$\bar{I}_1 = \frac{4\sqrt{R}}{1 - R} \overline{\cos^2 \frac{\psi}{2}} = \frac{2\sqrt{R}}{1 - R} \approx 32.$$

L'amplification globale est encore considérable.

Le P.F. réalise donc une accumulation considérable de flux lumineux à son intérieur, mais il faut noter que ce stockage de lumière ne se produit que pour les incidences d'accord de phase.

Lorsque l'incidence correspond à un minimum (très large) de la fonction d'Airy

$$Ay_{\min} = \frac{1}{1 + m} = \left(\frac{1 - R}{1 + R}\right)^2$$

le facteur de réduction $[(1 - R)/(1 + R)]^2 \sim 10^{-3}$ transforme cette concentration de lumière en raréfaction. Pour ces incidences, l'énergie du faisceau incident est en grande partie réfléchie et ne pénètre pas à l'intérieur de l'appareil.

Nous devons noter que le nombre de franges intérieures est donné par

* La différence de phase constante est due à la nature physique de la réflexion sur les plans réfléchissants. Elle ne fait que décaler le système de franges internes d'une cote constante Δz et nous la négligerons dans la suite.

† Nous supposons l'inclinaison i suffisamment petite pour qu'on puisse considérer les vibrations qui se composent comme des vibrations parallèles.

$$\frac{e}{\Delta z} = \frac{2ne\cos i}{\lambda} = k.$$

Il est égal à l'ordre d'interférence (qui diminue lorsque l'incidence i augmente). Le plan du milieu, plan de symétrie de l'appareil, est un plan nodal pour k pair, un plan ventral pour k impair. Cette remarque aura son importance dans la suite.

Etude de la Répartition de Phase dans les Franges Internes

Considérons (Fig. 1) un trièdre trirectangle $0xyz$, $0z$ étant normal aux plans du P.F., $0x$ et $0y$ parallèles à ce plan, $0x$ dans le plan d'incidence de l'onde incidente, $0y$ perpendiculaire à ce plan.

Les deux vibrations résultantes a et b des suites d'Airy qui se croisent en M peuvent être représentées par les expressions:

$$a\cos\omega\left(t - \frac{x\sin i - z\cos i}{c/n}\right)$$

$$b\cos\omega\left(t - \frac{x\sin i + z\cos i}{c/n}\right)$$

c, vitesse de la lumière dans le vide.

$\omega = 2\pi\, c/\lambda$, pulsation.

Négligeant la très faible différence entre a et b, la vibration résultante peut se mettre sous la forme:

$$A = 2ab\cos\frac{2\pi\, nz\cos i}{\lambda}\cos\omega\left(t - \frac{x\sin i}{c/n}\right).$$

La phase résultante est

$$\Phi = \frac{\omega x\sin i}{c/n} = \frac{2\pi}{\lambda}\cdot nx\sin i.$$

Dans l'expression de Φ ne figure que la coordonnée x.

La phase résultante reste constante le long de $0y$ et le long de $0z$. Avec cependant une réserve importante: d'une frange à la suivante, le facteur d'amplitude $\cos(2\pi nz\cos i/\lambda)$ change de signe, ce qui est équivalent à un changement de phase brusque de π. La phase est constante et indépendante de la cote z à l'intérieur d'une frange, mais deux franges consécutives vibrent en opposition de phase. (On remarque l'analogie avec les fuseaux d'une corde vibrante dans l'expérience de Melde.)

Lorsque le faisceau incident possède l'incidence normale ($i = 0$, $\sin i = 0$), la phase reste aussi constante le long de $0x$. Tous les points à l'intérieur du volume d'une frange d'interférence vibrent alors en accord de phase, et l'onde intérieure au P.F. constitute une "onde stationnaire." Si l'inclinaison i n'est pas nulle, la phase varie lentement dans une frange le long de $0x$, la vitesse de phase dans la direction $0x$ est $V = c/n\sin i$. L'énergie lumineuse se propage le long de $0x$, comme dans un guide d'onde, avec une vitesse de groupe faible (qui pour n voisin de l'unité est égale à $c\sin i$).

Nous pouvons remarquer que si des atomes se meuvent à l'intérieur d'un P.F. et interagissent avec la vibration lumineuse, *tant que ces atomes restent a l'intérieur du volume d'une même frange*, aucun effet Doppler n'est lié aux composantes v_y et v_z du vecteur vitesse de l'atome, il n'apparaît qu'un faible effet Doppler lié à la composante v_x, de grandeur $\Delta\nu/\nu = v_x/V = (v_x/c).n\sin i$. Ce résidu d'effet Doppler s'annule complètement lorsque l'onde lumineuse est normale au P.F. ($i = 0$).

Nous tirerons plus loin de ce résultat des conclusions importantes.

III. Emission d'Atomes Placés à l'Intérieur d'un P.F.

Nous allons maintenant aborder le problème qui nous intéresse, celui d'atomes se trouvant à l'intérieur de l'appareil, entre les deux faces réfléchissantes. Nous supposons que ces atomes émettent de la lumière (on peut, par exemple, les éclairer latéralement pour provoquer leur résonance optique). Les vibrations émises par les différents atomes sont supposées incohérentes. Le P.F. est supposé symétrique (constitué par deux faces semi-réfléchissantes identiques).

Considérons alors au point P à la cote z (comptée à partir du haut, Fig. 2) un petit élément de volume dv contenant Ndv atomes lumineux, et cherchons à évaluer l'intensité lumineuse rayonnée vers l'extérieur par la face inférieure, sous l'incidence i dans le plan $x0z$. Posons égale à l'unité l'intensité lumineuse d'un atome supposé isotrope.

Le rayonnement de l'élément de volume donne lieu à des rayons émergents qui se groupent en deux suites d'Airy dont les vibrations respectives ont les amplitudes relatives:

Suite a: t, tr^2, tr^4, ... etc.

Suite b: tr, tr^3, tr^5, etc.

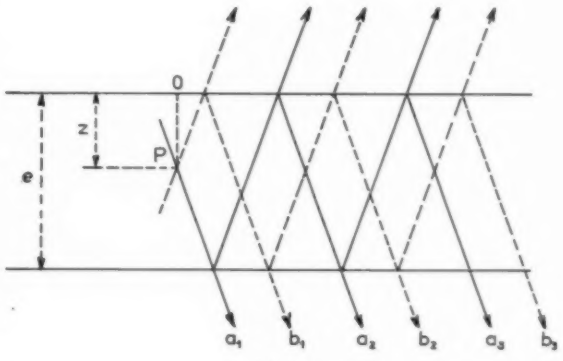

Fig. 2

Les amplitudes résultantes de ces deux suites sont représentées par:

$$a = Ndv \frac{t}{1 - r^2} \left[Ay(t) \right]^{1/2}$$

$$b = Ndv \frac{tr}{1 - r^2} \left[Ay(i) \right]^{1/2}.$$

Ces vibrations résultantes présenteront entre elles une différence de phase

$$\psi = \frac{2\pi}{\lambda} \cdot 2nz \cos i + C^{te}.$$

L'intensité résultante (observée dans un système de franges formé à l'infini) est donnée par l'expression:

$$dI = \left[(a - b)^2 + 4ab \cos^2 \frac{\psi}{2} \right] Ndv$$

soit, en négligeant comme précédemment le très petit fond continu:

$$dI \approx Ndv.\ 4ab \cos^2 \frac{\psi}{2}$$

$$= 4Ndv \frac{t^2 r}{(1 - r^2)^2} Ay\,(i) \cos^2 \frac{\psi}{2}$$

$$= 4 \frac{\sqrt{R}}{1 - R} Ay\,(i).N \cos^2 \frac{\psi}{2} dv.$$

Pour connaître la luminance totale B dans la direction i, il nous faut connaître la loi de répartition des atomes émetteurs dans l'espace intérieur et former la somme étendue au volume intérieur v.

$$BS = \frac{4\sqrt{R}}{1 - R} Ay(i) \int_v N(x, y, z) \cos^2 \left(\frac{2\pi}{\lambda} . nz \cos i \right) dxdydz.$$

Supposons la densité des atomes uniformes et posons $\int dxdy = S$, surface du P.F. Nous obtenons:

$$B = \frac{4\sqrt{R}}{1 - R} Ay(i)N \int_0^e \cos^2 \left(\frac{2\pi}{\lambda} nz \cos i \right) dz.$$

S'il y a un nombre entier de *franges dans* l'interface,

$$\int_0^e \cos^2 \left(\frac{2\pi}{\lambda} nz \cos i \right) dz = e.\overline{\cos^2 \frac{\psi}{2}} = \frac{e}{2}$$

$$B(i) = \frac{2\sqrt{R}}{1 - R} .Ne. \frac{1}{1 + m \sin^2 \varphi/2}.^*$$

Si l'espace interieur est rempli d'atomes uniformément luminescents, on observe de part et d'autre un système d'anneaux d'interférence dont la répartition d'intensité en fonction de l'angle d'inclinaison i est donné par la fonction d'Airy.

Si les faces terminales n'étaient pas réfléchissantes, la luminance (uniforme) du milieu serait:

$$B_0 S = \int_v Ndv = NSe.$$

Nous pouvons mettre $B(i)$ sous la forme:

$$\frac{B(i)}{B_0} = \frac{2\sqrt{R}}{1 - R} \cdot \frac{1}{1 + m \sin^2 \varphi/2}.$$

Avec les données numériques précédentes la brillance au centre des anneaux brillants est

$$\frac{2\sqrt{R}}{1 - R} B_0 = 32\ B_0.$$

Grâce a l'interposition des faces semi-réfléchissantes, l'énergie lumineuse émise par la couche luminescente, au lieu d'être uniformément répartie dans toutes les directions, est concentrée dans des anneaux fins et extrêmement brillants.

On peut remarquer qu'en rendant la face supérieure non utilisée du P.F. totalement réfléchissante ($R_1 = 1$, $R_2 = R < 1$), on rend les anneaux émergents de la face inférieure encore plus fins et encore plus brillants. On doit remplacer alors dans les formules précédentes r^2 par $r_1 r_2 = r_2 = r$.

Calcul de la Brillance Moyenne

Nous définirons la brillance moyenne par la relation:

$$\overline{B} = \frac{\int B(i) d\omega}{\Delta\omega}$$

ou $d\omega = 2\pi \sin i\, di = 2\pi d(\cos i) = C^{te}\ d(\varphi/2)$ est l'élément différentiel d'angle solide.

$$\overline{B} = \frac{\int B(i) d(\varphi/2)}{\Delta(\varphi/2)}.$$

Moyennons sur l'intervalle angulaire d'un anneau $\Delta(\varphi/2) = \pi$:

$$B = \frac{\int_{-\pi/2}^{+\pi/2} b(i) d(\psi/2)}{\pi}$$

$$= \frac{2\sqrt{R}}{1 - R} \frac{B_0}{\pi} \int_{-\pi/2}^{+\pi/2} \frac{d(\varphi/2)}{1 + m \sin^2 \varphi/2}$$

$$\int_{-\pi/2}^{+\pi/2} \frac{dx}{1 + m \sin^2 x} = \frac{\pi}{\sqrt{m + 1}} = \pi \frac{1 - P_c}{1 + R}$$

$$\overline{B} = B_0 . \frac{2\sqrt{R}}{1 + R} \approx B_0.$$

B/B_0 ne diffère de l'unité que d'un terme du second ordre en $\varepsilon = 1 - R$.

L'énergie totale rayonnée est conservée. Elle est la même qu'en absence de faces semi-réfléchissantes. Mais lorsqu'on interpose les faces semi-réfléchissantes, au lieu d'être rayonnée uniformément, elle est concentrée dans des anneaux fins et très brillants.

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* La notation $B\,(i)$ indique que B est une fonction de i.

IV. Distribution non Uniforme des Atomes Emetteurs Y. Cas d'un Jet Atomique à l'Interieur du P.F.

Supposons qu'au lieu d'utiliser une distribution uniforme d'atomes, on réalise à l'intérieur du P.F. un jet atomique, le plan moyen du jet étant parallèle aux faces du P.F. (plan $x0y$). La largeur et l'ouverture angulaire du jet sont déterminées par les largeurs de la fente source et de la fente sélectrice et par leur distance. Lorsqu'on emploie des fentes d'une largeur de 0.1 mm distantes de 10 cm les atomes s'écartent de leur direction moyenne d'un angle maximum de $\alpha = 0.1/100 = 10^{-3}$ radian. Si la vitesse thermique dans le jet est de l'ordre de $v = 10^4$ cm/sec et si la durée de vie d'un atome à l'état excité est de l'ordre de $\tau = 10^{-7}$ sec, l'atome parcourt pendant l'acte d'émission un chemin de $l\ v\tau = 10^{-3}$ cm $= 10\ \mu$ et subit pendant ce temps une dénivellation suivant $0z$ qui est au maximum de $\delta z = \alpha l = 10^{-2}\ \mu$, dénivellation qui reste petite par rapport à la largeur $\lambda/2n \cos i$ des franges.

La projection du chemin parcouru par les atomes dans la direction $0z$ reste petite par rapport à l'interfrange.

Pour de la lumière visible, l'interfrange est de l'ordre de 0.2 μ.

Notons que l'épaisseur du jet, de l'ordre de 0.1 mm = 100 μ est très grande vis-à-vis de l'interfrange. La somme

$$\int \cos^2 \frac{\psi}{2}\, dz \text{ est égale à } \overline{\cos^2 \frac{\psi}{2}} \cdot \varepsilon = \frac{\varepsilon}{2}.$$

ε étant l'épaisseur du jet.

Dans la formule donnant la brillance, le facteur $\int \cos^2 \psi/2\ dz$ peut donc être considéré comme constant.

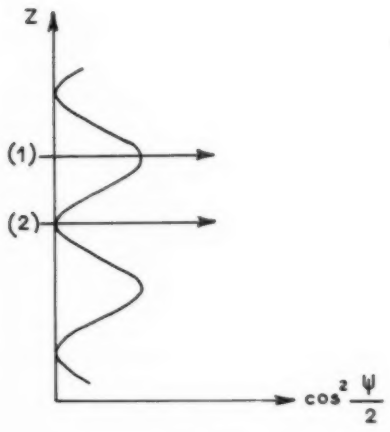

Fig. 3

Considérons alors pour une direction d'émission correspondant à l'accord de phase le système de franges internes. Si un atome émissif se meut au voisinage d'un plan ventral (Fig. 3, cas 1), il contribue fortement à l'émission sur le mode k considéré ($\cos^2 \psi/2 \sim 1$), mais il reste pendant l'acte d'émission à l'intérieur d'une même frange. L'émission d'un tel atome n'est pas affectée d'un déplacement Doppler. Cette conclusion est rigoureuse pour l'ordre d'interférence correspondant à la tache centrale ($i = 0$), elle n'est qu'approchée pour les anneaux $i \neq 0$, mais elle est encore convenablement satisfaite pour la partie de l'anneau située dans un plan $y0z$ normal à la direction moyenne du jet.

Considérons un autre atome qui se meut au voisinage d'un plan nodal (Fig. 3, cas 2). Un tel atome risque de passer d'une frange à la frange adjacente au cours de son acte d'émission et de voir alors la phase de son interaction avec l'onde changer brusquement de signe. L'émission d'un tel atome présente un effet Doppler, mais la contribution de cette émission au mode considéré est sensiblement nulle ($\cos^2 \psi/2 \approx 0$).

Dans l'ensemble, pour les atomes émetteurs dans le jet, l'effet Doppler est donc supprimé sur la tache centrale d'interférence. Lorsque l'ordre d'interférence est suffisamment élevé pour que la largeur de la tache soit déterminée non pas par la finesse instrumentale mais par la structure de la raie, *la largeur mesurée de la tache centrale doit correspondre à la largeur naturelle de la raie.*

Nous disposons donc là d'un moyen pour atteindre dans le domaine optique la largeur naturelle des raies spectrales. Notons que le nombre d'atomes émissifs dans un jet mince ne peut être que faible. Mais grace au facteur d'amplification du P.F., on peut espérer observer, même sur des jets très déliés, des anneaux d'une brillance suffisante.

Réglage de l'Appareil

Lorsque le plan moyen du jet fait un angle θ important avec le plan du P.F., on voit la tache centrale se dédoubler par effet Doppler. Ce dédoublement est symétrique. En plaçant le canon à jet sur un goniomètre et en observant ce dédoublement de part et d'autre de $\theta = 0$, en fonction de l'angle de rotation θ, on peut ainsi ajuster le montage exactement pour la valeur $\theta = 0$.

On sait que l'effet Doppler peut être fortement atténué en visant un jet ordinaire à angle droit de sa direction. On obtient dans ce cas aussi des anneaux fins.[5] Mais l'effet Doppler résiduel dû à l'ouverture angulaire finie du jet subsiste et l'on n'est pas à l'abri d'un déplacement dissymétrique de la raie, dû à une erreur d'orthogonalité.

Lorsque par contre le jet est à l'intérieur d'un P.F., l'effect Doppler résiduel et la dissymétrie sont sup-

primés. On doit noter l'intérêt de ce dispositif pour la métrologie.

V. Distribution non Uniforme des Atomes Émetteurs. Constitution d'un Réseau Excitateur Lamellaire

Au lieu de considérer une distribution uniforme d'atomes émetteurs entre les 2 plans réfléchissants, considérons une distribution du type:

$$N(z) = N_0 \cos^2 \beta z.$$

La brillance rayonnée prend alors la forme:

$$B = C^{te} \int_0^e \cos^2 \beta z \cos^2 \frac{\psi}{2} dz.$$

$$\text{Posons } \frac{\psi}{2} = \frac{2\pi}{\lambda} 2nz \cos i = \alpha z.$$

$$B = C^{te} \int_0^e \cos^2 \alpha z \cos^2 \beta z \, dz.$$

Pour $\alpha \neq \beta$, cette intégrale a pour valeur $^1/_4\, e$.* Pour $\alpha = \beta$, elle a pour valeur $^1/_4\, e.\ ^3/_2$.

On favorise donc ainsi l'ordre d'interférence k pour lequel la condition $\alpha = \beta$ est réalisée, c'est-à-dire celui pour lequel la répartition sinusoidale des atomes épouse le système de franges.

L'anneau interférentiel correspondant est 1.5 fois plus intense que les autres anneaux.

Moyen Experimental pour Réaliser une Telle Répartition

Supposons l'intervalle du P.F. rempli d'une substance fluorescente capable d'émettre une radiation monochromatique λ, et supposons réalisée la condition $2ne = k\lambda$ de façon qu'il y ait accord de phase pour l'émergence normale $i = 0$.

Supposons l'appareil éclairé à travers la face de dos par une radiation monochromatique $\lambda' < \lambda$ susceptible d'exciter la fluorescence. Sélectionnons dans le rayonnement excitateur par un diaphragme annulaire fin† (Fig. 4) une incidence i' telle que:

$$\frac{n' \cos i'}{\lambda'} = \frac{n}{\lambda}.$$

La radiation excitatrice forme alors à l'intérieur du P.F. un système de franges:

$$\cos^2 \beta z = \cos^2 \frac{2\pi}{\lambda'} n'e \cos i'$$

qui réalise un "réseau lamellaire" d'excitation pour la fluorescence. La condition $\alpha = \beta$ se trouve ainsi réalisée.

La fluorescence donne lieu à un système d'anneaux à l'extérieur, et dans ce système, la tache centrale est 1.5 fois plus intense que les autres anneaux. On peut évidemment favoriser l'émission d'un autre ordre d'interférence $2ne \cos i = (k - p)\lambda$ en réalisant la condition:

$$\frac{n' \cos i'}{\lambda'} = \frac{n \cos i}{\lambda}.$$

Un tel dispositif peut présenter un intérêt pour déclencher l'émission induite d'un "Laser" sur un mode déterminé.

On peut par exemple consituter un P.F. avec un cylindre de rubis et former à l'intérieur de ce cylindre le système de franges de la raie verte d'un arc au mercure basse pression. L'étendue angulaire faible de cette irradiation fournira sans doute un flux lumineux insuffisant pour déclencher l'émission induite. Mais lorsqu'on déclenche celle-ci par l'addition d'une irradiation latérale puissante, elle peut fournir l'appoint nécessaire pour favoriser le déclenchement de l'émission induite sur le mode qu'elle renforce.

VI. Atomes Absorbants à l'Intérieur d'un P.F.*

Nous avons étudié à l'intérieur d'un P.F. le comportement d'atomes émetteurs. Il nous faut envisager aussi le cas d'atomes intérieurs qui absorbent l'énergie d'une onde lumineuse qui traverse un P.F. Lorsque la densité des atomes est grande et lorsque cette absorption est forte, on pressent que la répartition même de l'énergie lumineuse entre les plans réfléchissants peut se trouver profondément perturbée et modifiée par la

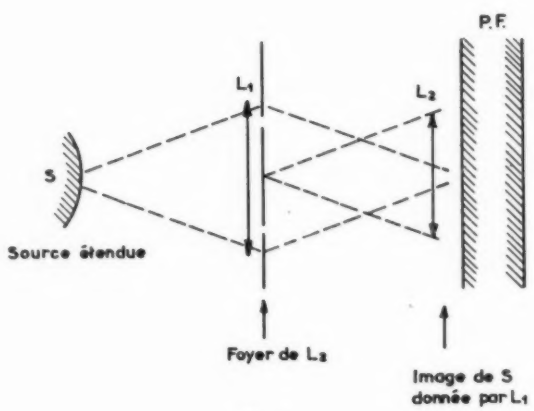

Fig. 4

* Si l'intervalle e correspond à un nombre entier de franges, c'est-à-dire pour les directions i d'accord de phase.

† et au besoin par une présélection à l'aide d'un P.F. auxiliaire.

* D. A. Jackson a rèalisi rècemment une expérience d'absorption sur des atomes placés à l'intérieur d'un P.F. [Proc. Roy. Soc. **A263**, 289 (1961)].

présence des atomes et par leur réaction avec l'onde. Nous allons nous borner au cas où l'absorption est supposée assez faible pour que cette perturbation soit petite. On trouve alors des résultats analogues à ceux établis pour l'émission. Lorsque les atomes absorbants sont ceux d'un jet parallèle au plan du P.F., l'effet Doppler est supprimé et les franges obtenues, la tache centrale en particulier, sont extrêmement fines. Si les raies de la source sont déjà assez fines pour permettre l'emploi d'un ordre d'interférence élevé à la limite du recouvrement des anneaux, les franges d'absorption des atomes du jet se détacheront comme anneaux noirs très fins au milieu des anneaux d'émission élargis de la source. Ces anneaux présenteront un petit glissement Doppler parallèlement à la direction du jet, proportionnel à sin$i$. La tache centrale noire n'en est pas affectée.

Envisageons également le cas d'un milieu absorbant uniformément réparti et essayons d'évaluer dans ce cas la grandeur de l'absorption afin de pouvoir la comparer à l'absorption de la même couche d'atomes pour une onde progressive.

Considérons les rayons d'une suite d'Airy qui traversent le P.F. et qui parcourent à l'intérieur des chemins successifs e, $3e$, $5e$, etc. (nous supposons cos i voisin de 1). Entre deux réflexions successives, chacun de ces rayons subit l'affaiblissement d'intensité $I' = Ie^{-ke} \sim I(1 - ke)$ si k est petit.

L'affaiblissement correspondant de l'amplitude est donné par:

$$a' = ae^{-k/2e} = a(1 - k/2\,e).$$

Posons $\rho = 1 - (k/2)e = 1 - \varepsilon$, ε étant petit devant l'unité. Nous pouvons représenter les amplitudes de la suite d'Airy par $t\rho$, $t\rho^3r^2$, $t\rho^5r^4$, etc.

Cette suite est l'équivalent d'une suite correspondant à un coefficient de transmission $t' = t\rho$ et à un coefficient de réflexion $r' = r\rho$ avec $t'^2 + r'^2 < 1$.

L'intensité résultante dans les anneaux transmis est alors:

$$I' = \frac{t'^4}{(1 - r'^2)^2} \cdot \frac{1}{1 + m' \sin^2 \varphi/2}.$$

Par suite de l'absorption interne les franges sont à la fois affaiblies et élargies ($m' < m$). Ceci montre que le coefficient d'absorption apparent n'est pas constant, mais qu'il croît lorsqu'on s'approche du centre d'une frange brillante.

L'intensité au centre d'un anneau brillant devient

$$I'_0 = \frac{t'^4}{(1 - r'^2)^2} = \frac{t^4\rho^4}{(1 - r^2\rho^2)^2}.$$

En remplaçant ρ par $1 - \varepsilon$ et en ne retenant dans le développement que les termes du 1er ordre en ε, il vient:

$$I'_0 = \frac{t^4}{(1 - r^2)^2}\left(1 - \frac{4\varepsilon}{1 - r^2}\right) = 1 - \frac{4\varepsilon}{1 - R} = 1 - \frac{2ke}{1 - R}$$

Nous pouvons définir un coefficient d'absorption apparent K par la relation $I'_0 = 1 - Ke$.

L'identification donne $K = 2k/(1 - R)$.

Pour $R = 0.94$ et $1 - R = 0.06$, nous voyons que le coefficient d'absorption se trouve amplifié au centre des anneaux brillants par un facteur de l'ordre de 30. Il est donc possible avec des milieux très dilués d'observer une absorption déjà très notable. Pour obtenir la même absorption sur une onde progressive, il faudrait employer un milieu absorbant trente fois plus épais ou trente fois plus dense.

Bien entendu un tel raisonnement grossier n'est plus valable lorsque l'absorption est forte.

Lorsqu'on utilise l'interféromètre à des ordres d'interférences élevées où la résolution fait apparaître la structure des raies d'émission et d'absorption, il faut considérer le coefficient d'absorption k comme une fonction de la longueur d'onde à l'intérieur de chaque anneau. Le calcul de la structure de la raie transmise en présence d'atomes absorbants est alors un problème qui n'est pas simple. Nous ne l'aborderons pas ici. Pour déterminer cette structure, il y a lieu de tenir compte également de la dispersion anormale, c'est-à-dire de la variation rapide de l'indice de réfraction n sur les bords de la raie d'absorption.

Nous venons d'examiner les caractères d'émission et d'absorption d'atomes situés à l'intérieur d'un P.F., entre les deux plans réfléchissants. Lorsqu'il en est ainsi les ondes réfléchies successives reviennent sur l'atome dans un temps qui est court par rapport à sa durée d'émission, à la condition que l'épaisseur e du P.F. soit assez faible pour conserver la cohérence des divers trains d'onde émergents. Il se produit alors nécessairement une interaction entre l'atome et son propre champ de rayonnement et l'on peut dire que c'est ce couplage qui modifie le diagramme de rayonnement de l'atome. Au lieu d'être isotrope comme celui d'un atome isolé, il se fait dans des directions privilégiées. Nous avons cependant admis que ce couplage ne modifie pas la durée de vie d'un atome. Ceci est probablement vrai, mais en première approximation seulement. Une théorie complète de cette interaction dans le cadre de la théorie quantique des champs doit permettre d'examiner ce point et de préciser les propriétés du couplage entre l'atome et son propre champ de rayonnement.

Les considérations précédentes restent très schématiques. Nous avons admis qu'un atome à l'intérieur d'un Perot-Fabry a ou bien des propriétés émissives ou bien des propriétés absorbantes. En réalité les atomes possèdent ces deux propriétés à la fois, et le rapport entre le pouvoir émissif et le pouvoir absorbant est régi par la loi de Kirchhoff, qui fait intervenir la température du milieu, c'est-à-dire pour une raie spectrale donnée le rapport entre la population du niveau supérieur et du niveau inférieur. Si ce rapport est inférieur à l'unité, la brillance d'une couche émissive

et autoabsorbante ne peut dépasser celle du corps noir à la même température, mais cette limite est atteinte très rapidement. Si ce rapport est supérieur à l'unité, les conditions correspondent à une température absolue négative. Ce sont précisément les conditions qui conduisent au déclenchement de l'émission induite.

En conclusion, nous espérons avoir montré que les propriétés d'un interféromètre Perot-Fabry, à l'intérieur duquel se trouve de la matière émissive ou absorbante, sont intéressants et méritent de faire l'objet de recherches expérimentales. L'application de ces propriétés au fonctionnement d'un LASER est d'actualité, mais ce n'est pas la seule application utile d'un tel système. La possibilité de production de franges d'interférence très fines dans un cas (jet) ou très intenses dans un autre (milieu uniforme) peut intéresser la métrologie d'une part, l'exploration de la structure des raies d'autre part.

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Photo D. L. MacAdam

Were you there? Some of the participants in the July 1961 ICO London Meeting.

Were you there? Some of the participants in the Paris ICO meeting July 1961

Photo: Harand

Synthetic Maser Ruby

Robert D. Olt

Synthetic ruby, which is single crystal aluminum oxide doped with chromium oxide, is being extensively used in several solid state devices, including microwave masers, coherent light oscillators (optical masers or lasers), and a new phonon-type acoustical maser. This paper describes the physical properties of synthetic ruby which are pertinent to its use in solid state applications.

Physical Properties

C. H. Townes of Columbia University conceived the principle of microwave amplification by stimulated emission of radiation in 1951, and later applied it in the first operational ammonia beam maser. In 1956, Townes,[1] Bloembergen,[2] and others suggested uses of solid state materials in various microwave masers. Geusic,[3] Kikuchi,[4] and several others[5,6] further investigated the paramagnetic properties of ruby as a maser material because of its physical and chemical stability, high thermal conductivity, and low dielectric losses. Recent extensions of ruby investigation include:

a. Maser operation at temperatures as high as 195°K.[7]

b. Achievement of X-band operation having a 14 Mc gain-bandwidth at 77°K.

c. Using 55° whole annealed ruby, a gain-bandwidth of 100 Mc at 1.4°K and 35 Mc at 4.2°K (in a field of 4000 gauss pumped with about a milliwatt of power at 23.1 kMc, signal at 9.14 kMc, 30°K noise figure).[8]

d. Traveling wave maser using a 8.4 cm long annealed ruby slab operating at L-band having a gain of 6.5 db at 1250 Mc (±10% tuning range), and S-band gain of 9.1 db at 2250 Mc (±6% tuning range), liquid helium temperature.[9]

e. Iron-doped sapphire used in a zero-field device.[10]

f. Chromium-doped rutile (TiO_2)[11] used in a 9 kMc maser, pumped at 34 kMc, having a gain-bandwidth product of 25 Mc at 4.2°K.

g. Comprehensive summary of masers, as well as Siegman's design matrix elements and energy levels of ruby, are given by Weber.[12]

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h. Cooled optical masers having line widths as low as 0.08 cm^{-1} and threshold energies of 240 joules in disc ruby (vs. up to 2300 joules in large, long, conventional ruby) and as low as 48 joules for the ruby overlay, in reasonably comparable systems.

Schawlow and Townes[13] further proposed the extension of the solid state amplification concepts to higher frequencies. Maiman, in late 1959, observed the narrowed (<1 A) ruby fluorescence band[14–16] at 6943 A, having a peak power of about 10 kw and a total energy of over 1 joule, in a 0.05% final whole annealed dilute pink ruby cube. Collins *et al.*[17] further confirmed the coherence and directionality of the stimulated light emission. The Bell Telephone Laboratory group used a zero degree annealed conventional dilute ruby rod, 0.5 cm in diameter by 4.0 cm long, with the ends polished flat to $^1/_{10}$ Na band and parallel to 18 seconds, silvered to transmit 1–5%. The xenon flash lamp operated above 4000°K through a capacitor discharge of 400 μf at 4 kv. A 1000-fold light intensity increase was observed at a threshold of about 2000 joules having an effective temperature of 10^{10}°K through an angle of 0.3 deg at 14,400 cm^{-1}. Lineage in the crystal varied ±1° about the cylindrical, or optical, axis. Schawlow[18] further observed pulsed optical maser activity in a 0.5% final annealed ruby rod at about 7009 A and 7041 A at liquid nitrogen and colder temperatures. Ruby has optical absorption at 5600 A (green), 4150 A (violet), and to a lesser extent—but more sensitive to concentration—at 4750 A. Otherwise the properties of ruby are similar to those of synthetic sapphire.

Ruby Development

Hughes Research and the Bell Telephone Laboratories did their early work using the conventional ruby boule grown by techniques similar to the original

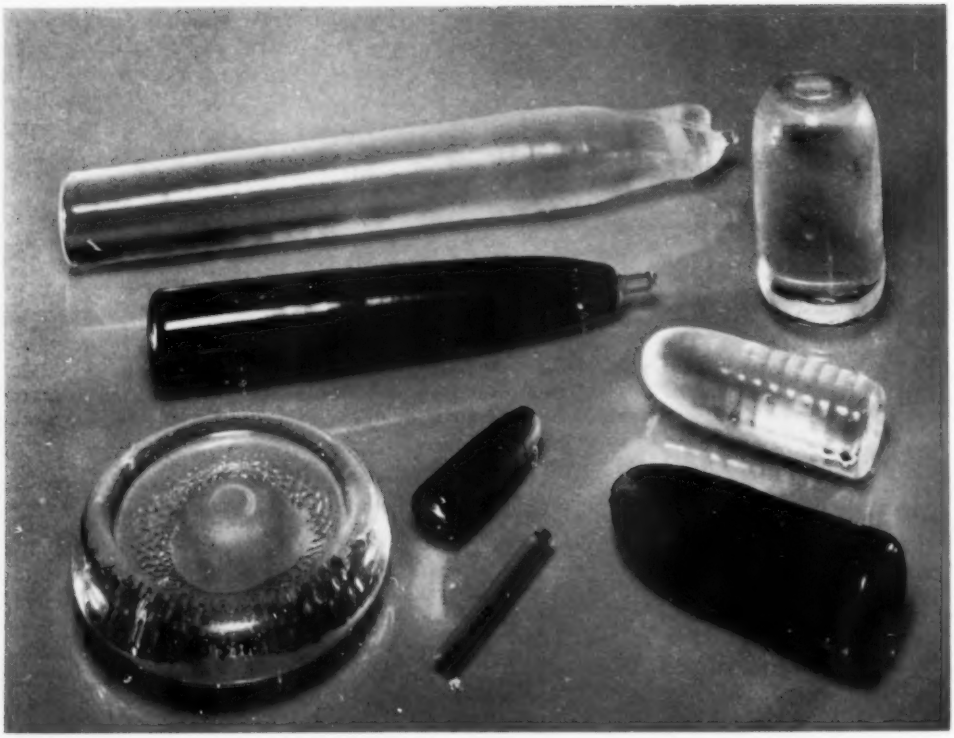


Fig. 1. Various results of different Verneuil growth techniques, showing conventional boules lower right corner, a barrel boule upper right, spiral sapphire and ruby upper left, disc boule lower left, rutile boule in center, and a fabricated optical maser rod 5 mm in diameter by 50 mm long in front center.

August Victor Louis Verneuil flame fusion technique developed in 1904. This material, grown by European or Linde volume production techniques, was cooled to near liquid nitrogen temperatures, and operated in a cylindrical optical cavity. Threshold energies of about 2300 joules and a line width of 0.3 cm^{-1} were common. It was apparent that significant improvement was necessary in internal crystal homogeneity to improve both the spectral purity of the optical maser output, as well as to reduce the energy required (part of which has to be removed), in the quest for reasonable technical approaches to continuous wave operation. The main problem to be solved in the high temperature flame fusion process was to reduce the mechanical and optical strain induced in the crystal during growth. The more important parameters in low strain ruby are minimum thermal gradients, as the Cr_2O_3: Al_2O_3 solid solution moves through the solidus–liquidus phase into the solid phase, and as the resultant crystal thermally contracts while cooling to room temperature. These thermal gradients approach a minimum at the equilibrium rate of growth, which actually can be a higher rate than conventional ruby grown in the United States. Consequently, the term "slow-grown" is merely relative to the different growth processes available and does not relate to the amount of strain in an as-grown crystal. For conventional crystals, annealing, in fact, introduces internal discontinuity in ruby, both by allowing impurities to precipitate in sapphire lattice vacancies, as well as allowing molecular translation with subsequent increased crystal misorientation. The first domestic improvement in conventional ruby was the spiral ruby primarily intended for the long length traveling wave maser. Comparable optical measurements in this crystal indicate a threshold energy level of the order of 340 joules, and a line width of the order of 0.18 cm^{-1}. A major breakthrough again developed in the disc boule growing process, where temperature gradients are reduced to about $^1/_{10}$ of the lowest of either of the previous processes, and threshold energies of 120–240 joules with line widths of 0.12 to 0.08 cm^{-1} were quite common among disc material.

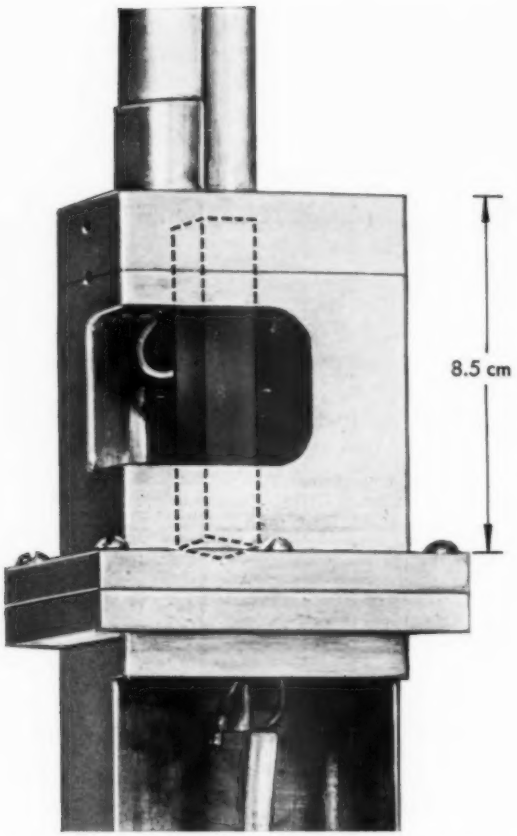
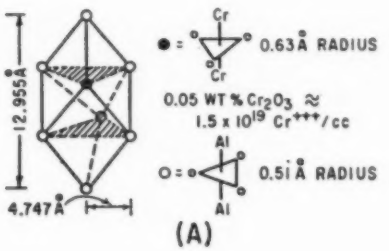


Fig. 2. Airborne Instruments tunable cavity ruby maser.

Fig. 3. Bell Telephone Laboratory traveling wave ruby maser.



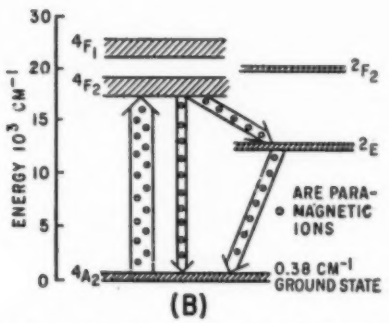


Fig. 4. Ruby unit cell (A) and energy level diagram (B) for optical maser.

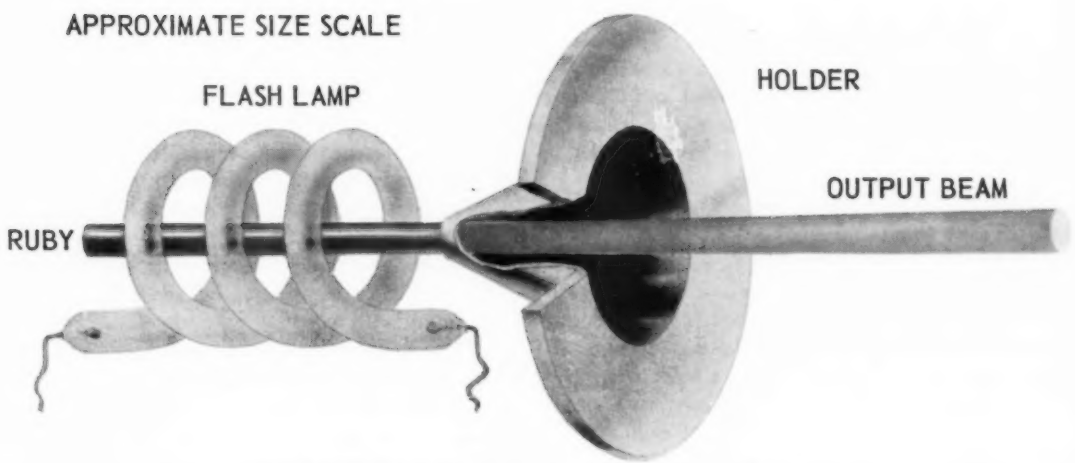


Fig. 5. Bell Telephone Laboratory pulsed ruby optical maser.

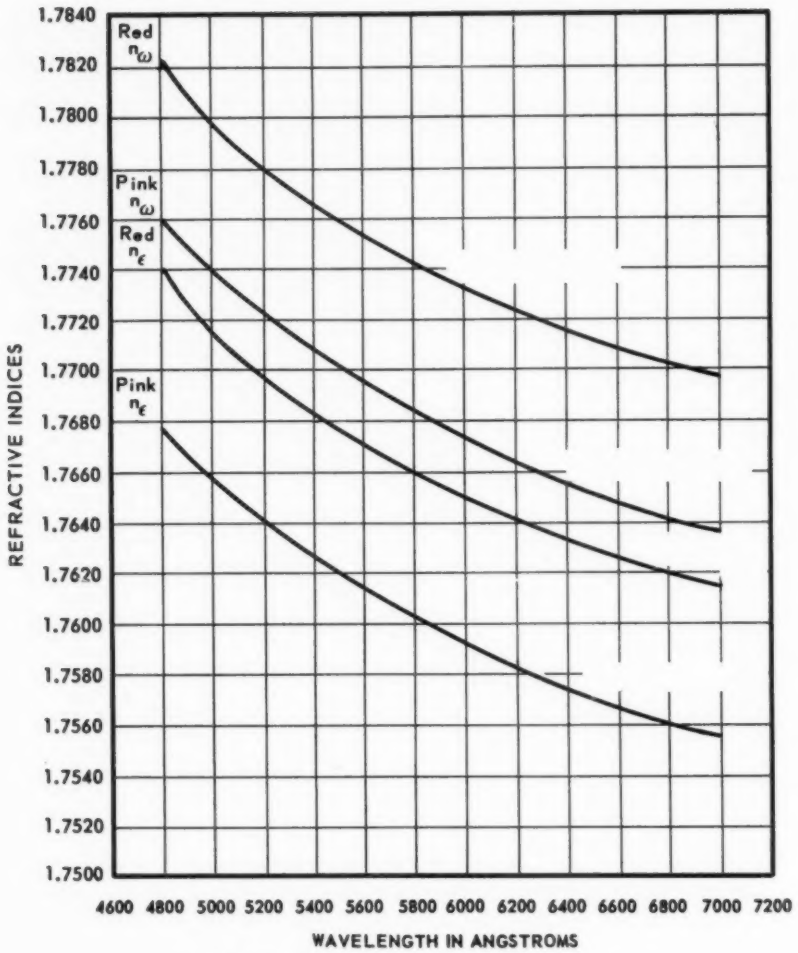


Fig. 6. Refractive indices of synthetic ruby.

Improved flatness and parallelism of the optically polished ends also contribute to increased ruby efficiency and improved beam characteristics. Recent measurements were made by Dr. C. E. Luck at Raytheon Company to determine the threshold and beam divergence as a function of flatness and parallelism. Three Linde ruby crystals, indentical in every respect except the controlled deviations, were fabricated by Valpey Crystal Corp. (Holliston, Massachusetts) and then silvered simultaneously so that the corresponding end coatings would be identical. The ruby rods which were each mounted in the focus of an elliptical cylinder reflector, having the flash lamp at the other focus, exhibited laser action with a reduction in threshold pump energy of about 20% in a rod having 2 second end parallelism, compared to a rod having a 15 second end parallelism. A substantial reduction in the resultant beam divergence of nearly 50% was observed in a rod having an end flatness of $\lambda/10$ compared to a rod with an end flatness of $1.0/\lambda$.

The next significant development in ruby optical masers was announced in London on July 14, 1961 by Dr. A. L. Schawlow, disclosing his conceived and a Linde-grown composite maser crystal involving a 2 mm diameter ruby core with a 1.5 mm sapphire sheath. Because of the optical focusing of the periphery of a standard 5.1 mm diameter ruby rod, most optical maser activity actually took place toward the core. The sapphire sheath served to perform the same optical focusing action, giving a larger optical capture cross section, but with the previous optical absorption in the green pumping spectrum reduced. This further reduced energy absorption in the periphery of the 5.1 mm diameter rod, which allowed cooler operation. The exposed sapphire cooling area reduced the thermal flux necessary to be transmitted into the cooling gaseous interface compared to the equivalent 2 mm ruby. At these liquid nitrogen temperatures sapphire actually

has a higher thermal conductivity than copper. Early measurements of the ruby overlay configuration indicate a threshold energy of 48–78 joules.

Coloring in ruby is associated with the trivalent chromium ion, Cr^{+++}, which is introduced into the crystal lattice during growth. In dilute or pink ruby, used in uncooled optical maser applications, the chromium is present in about 0.05–0.06 wt % Cr_2O_3: Al_2O_3 (1.6×10^{19} ions/cc). The introduction of the chromium ion, with an ionic radius somewhat larger than that of the aluminum ion, results in lattice strain which increases with chromium ion concentration. At higher chromium ion concentrations it becomes more difficult to produce ruby boules by the Verneuil technique with a low level of internal discontinuity. Since the Verneuil process requires melting of the aluminum oxide (2050°C), thermal stresses present a problem. Linde is currently developing modified growth techniques which yield an optical quality ruby with decreased thermal stresses. This is then followed by a long cycle annealing operation in which the crystal is brought to a temperature approaching the melting point.

Several internal imperfections are discernible in ruby: fuzed layers, seed crystals necessary to control orientation, entrapped gases, and lineage. Fuzed layers are caused by incompletely melted powders pulsed onto the boule growing cap. Some optical differences are evident between the seed chromium concentration of an incompletely melted seed crystal, and the remaining crystal. Lineage, or internal orientation variation, is easily observed between crossed polaroids, and is a result of substituted chromium strain and thermal stress. Synthetic ruby is birefringent and any slight internal misorientation is exhibited by differing light refraction through a crystal. If internal strain is unusually severe, twinning and fracture can result. These internal properties exist in a ruby crystal to a varying degree. Conventional European type ruby boule has lineage variations of several degrees; whole annealed conventional dilute ruby has a line width of about 0.3 wave numbers, and recent growth developments have yielded material of 0.19 wave number line width, with several at 0.12 to as low as 0.08 wave number.[18] No conclusive evidence is available indicating a prohibitive effect on the operation of microwave masers of minor fuzed layers, seed marks, gas entrapment, or lineage.[19] Linde optical quality ruby, grown with new process modifications, contains a minimum of these imperfections.

Costs

Ruby boules have been furnished to the gem-stone trade for many years; domestic ones having only chromium impurity while others, mainly European, have additional doping. Linde stocks only chromium-doped ruby boule in 0.05 pink, 0.5 and 0.7% standard, and 1.5% extra dark, approximate final weight concentrations. These are of random (generally about 60 deg) orientation, are carrot shaped, and can be as large as 1.6 cm in diameter at the widest point and up to 7.6 cm long. Smaller conventional boules begin at about $15 each as grown, whole annealed, and go up to the most recent low strain optical ruby, ranging from $200 to $500 each. It is difficult to have both maximum diameter and length in the low strain optical maser quality boule, although they are available for microwave applications. Boules selected to furnish a specified larger size are available at a premium. Currently, widely used maser concentration ruby boules are stocked in various orientations and sizes.

Linde has also produced doped sapphire and rutile and is currently working on other host crystals of specified orientation, concentration, and, in larger sizes than described, on special order. Since larger boules of specified orientation are more difficult to grow, costs increase for crystals of both specified higher concentration and orientation. Normally, the starting powder concentration is guaranteed.

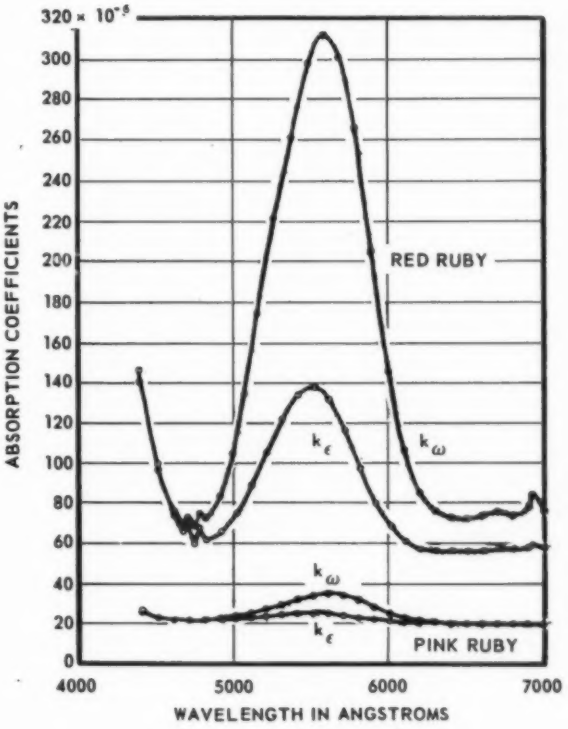


Fig. 7. Absorption of ruby.

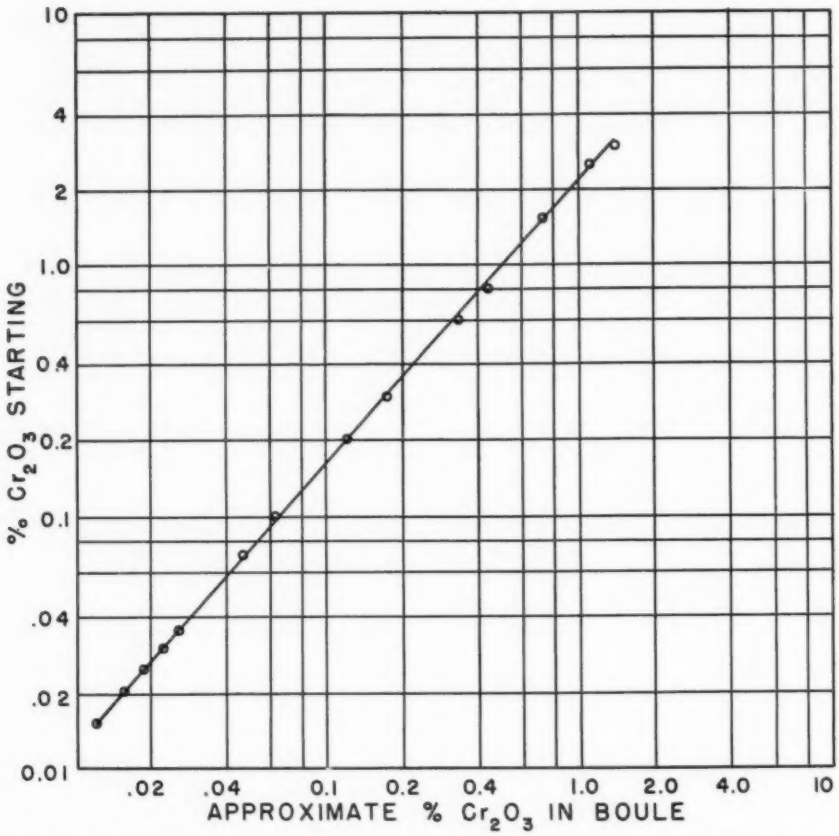


Fig. 8. Retention of pre-coprecipitated starting doping during Verneuil growth of ruby.

Fig. 10. Most recently developed low strain solid ruby for optical maser.

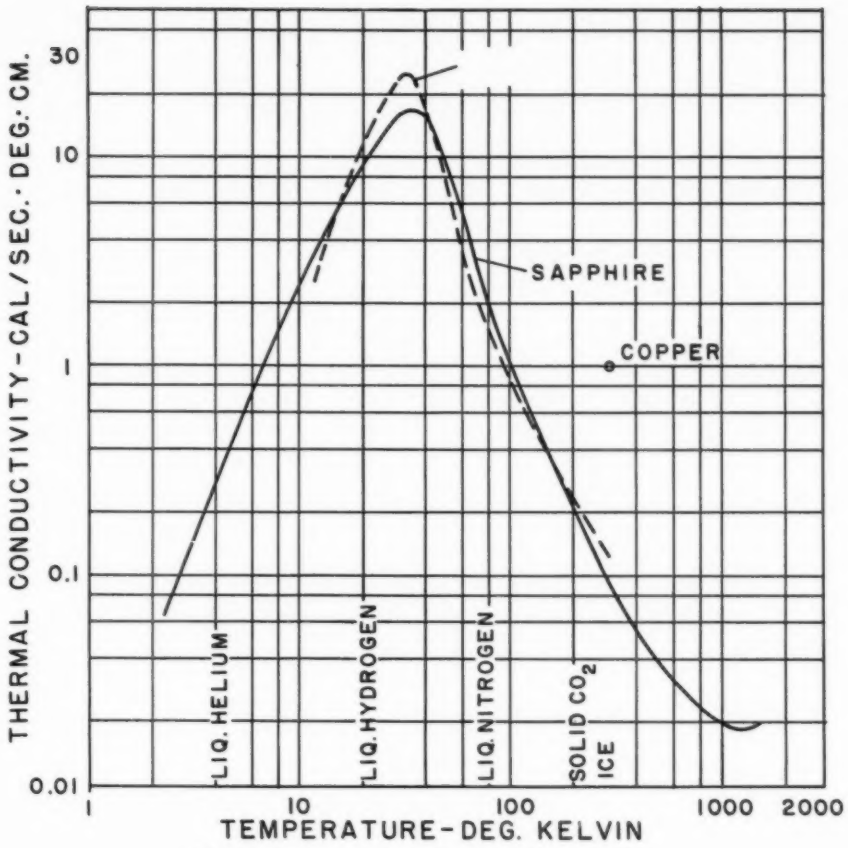


Fig. 9. Thermal conductivity of sapphire and ruby.

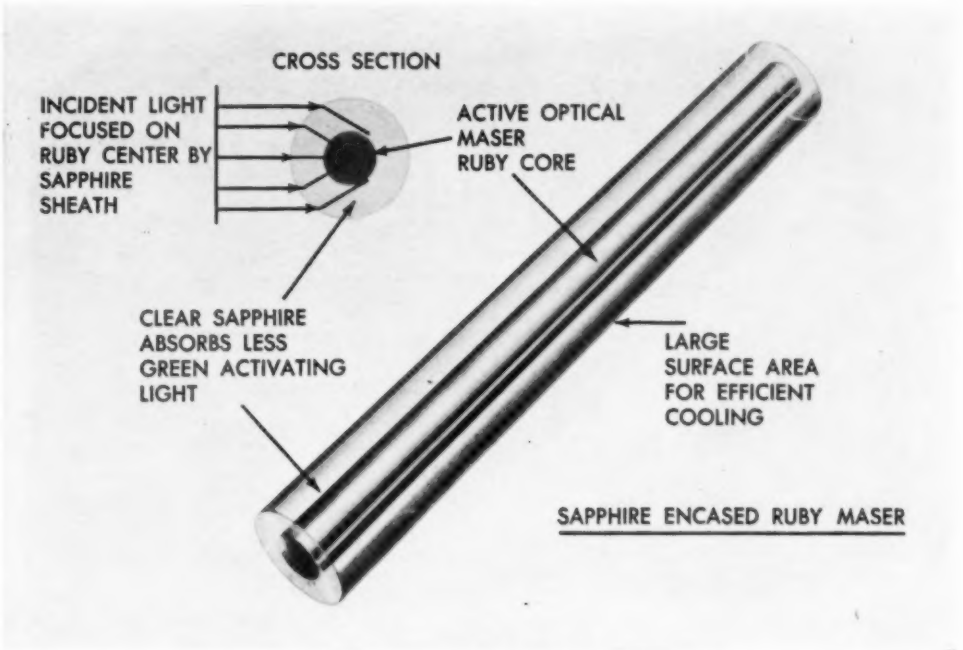

CROSS SECTION
INCIDENT LIGHT FOCUSED ON RUBY CENTER BY SAPPHIRE SHEATH
ACTIVE OPTICAL MASER RUBY CORE
CLEAR SAPPHIRE ABSORBS LESS GREEN ACTIVATING LIGHT
LARGE SURFACE AREA FOR EFFICIENT COOLING
SAPPHIRE ENCASED RUBY MASER

Fig. 11. Ruby composite crystal with sapphire overlay.

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OSA CORPORATION MEMBERS *continued from page 16*

BAUSCH AND LOMB INC., Rochester 2, New York, *founded in 1853, is a fully integrated manufacturer of ophthalmic products and scientific instruments. Eyewear and related diagnostic and prescription equipment account for roughly half of the sales. The product line also includes a wide range of instruments for analytical, industrial, medical, educational, motion picture, and military use; optical glass, lenses, mirrors, and reflectors. In addition, research and development programs are underway in several areas of electronics and radiation measurements, and basic studies are carried out on the effects of radiation on glass.*

BECKMAN INSTRUMENTS, INC., 2500 Fullerton Road, Fullerton, California, *manufactures electronic instruments, systems, and components for analysis, measurement, and control. Founded in 1935 with the first commercial pH meter, the Company soon introduced its first precision optical instrument, the spectrophotometer. Today more than 400 Beckman products serve throughout the world in scientific, industrial, medical, and space applications; and in addition to manufacturing facilities in Fullerton, Germany, and Scotland, the Company has sales and service representatives in most of the key cities of the United States and in 50 foreign countries.*

BELL AND HOWELL COMPANY, Chicago, Illinois

BELL TELEPHONE LABORATORIES, INC., New York, New York, *research and development unit of the Bell System. Its basic function is advancing the technology behind Bell System communications. The activity is broad, ranging from fundamental research (which created the transistor) to the engineering of complete systems (such as the transcontinental microwave system). Activities for national defense are exemplified by the development of the Nike-Hercules System, and the Command Guidance System used for the Titan missile and satellite orbiting vehicles.*

BENDIX CORPORATION, Detroit, Michigan, *began in 1929 with an original output of a handful of products, the most important of which were starter drives and four-wheel brakes; today the Corporation develops and produces hundreds of diversified products. In addition to the original automotive component line, the Corporation is a major factor in communications, instruments, computers, nucleonics, detection, and missile systems development and manufacture. In 1960, Bendix's engineering expenditures aggregated $120,000,000 of which 54% was research and development contracts, on a sales volume of $792,000,000.*

CHICAGO AERIAL INDUSTRIAL, INC., Barrington, Illinois; *its precision optical capability has been enhanced through the acquisition of Pacific Optical Corporation, Inglewood, California. Specialists in precision high acuity lenses for reconnaissance cameras, Pacific Optical provides optical system knowledge to complete CAI's full circle capability in optics, mechanics, and electronics. Utilizing long-time knowledge of sophisticated plastics, Pacific Optical engineers are developing viewing ports for supersonic aircraft and space vehicles. Other work is the development of infrared systems, optical elements for ultra-fast readout of data processing cards, wide angle cartographic lenses, and group projection systems for ground stations monitoring data transmissions from orbiting space vehicles.*

CORNING GLASS WORKS, Corning, New York, *manufacturer of specialty glasses, was founded in 1851. The basis of company growth has been the development of new materials and new products for use in science, industry, and the home. In 1908 Corning founded a research and development laboratory, and formulas for more than 75,000 different types of glass have been recorded since that time. Process developments have included the mass production of optical glass in 1944 and subsequent manufacture of a wide range of optical and ophthalmic glasses.*

DAVIDSON MANUFACTURING COMPANY, INC., West Covina, California

E. I. DUPONT DE NEMOURS AND COMPANY, INC., Central Research Dept., Experimental Station, Wilmington, Delaware, *founded in 1802 to supply powder for a young nation's needs, the Du Pont Company today makes several thousand chemical products at 78 plants in 28 states. At the Experimental Station and at more than 40 other laboratory sites, Du Pont spent $96 million on research and development in 1960. About half its sales in recent years represent products of research introduced commercially within the past 25 years.*

continued on page A18

Proposal for an Electron Accelerator Using an Optical Maser

Koichi Shimoda

Among many possible applications of the extremely high brightness temperature and the radiation density obtainable with the optical maser, a high energy electron accelerator is proposed and discussed in this paper. It consists of a cylindrical tube of maser material excited by a pumping radiation through an interference filter coated on its outer surface and, it generates an oscillation in a TM_0NM type mode. An optical peak power of 10 kw/cm² was calculated to accelerate electrons by 10^9 ev/meter. A gas-filled cavity is proposed for velocity matching. Selection of the particular mode might be made by placing a periodically printed absorption layer on the inner surface of the maser cylinder. However, mode separation would be extremely difficult because of thermal expansion of the maser material.

I. Introduction

Directivity, coherence, and brightness temperature of the radiation generated by a high frequency maser are described by the extremely narrow spectral width of the oscillation. When the effect of saturation is neglected, the theoretical width of the spectrum of maser oscillation is given approximately by

$$\delta\nu = \frac{4\pi kT_n(\Delta\nu)^2}{P}, \tag{1}$$

where $\Delta\nu$ is the spectral width of the line at the absence of maser action, P is the output power, and kT_n is the noise energy, calculated from the theory of noise in masers[1] to be

$$kT_n = h\nu_0 \frac{N^*}{N^* - N'} = \frac{h\nu_0}{1 - \exp(h\nu_0/kT_e)}. \tag{2}$$

Here $-T_e$ is the effective negative temperature representing the ratio of populations N^* and N' in the upper and lower states respectively. Note that the spectral width of an oscillation given by Eqs. (1) and (2) holds even when $h\nu_0 \approx kT_e$ if the oscillation occurs in a single mode. An oscillation in a multimode resonance has a broader width which is roughly proportional to the multiplicity.

Since the large output power from an optical maser is concentrated in its narrow width, the brightness temperature is extremely high so that it can produce very high electric and magnetic fields at the optical frequency. Among many possible applications of an extremely high radiation density obtainable with the optical or infrared maser, an electron linear accelerator is proposed here.

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II. Field in a Cylindrical TM_{0NM} Cavity

A cylindrical tube of maser material is pumped through an interference filter which is coated on its outer surface in order to reflect the signal wave and to transmit pumping radiation as shown in Fig. 1. When the cavity resonator is operated in a TM_{0NM} type mode, N and M being very large, the maximum electric field is produced along the axis of the cylinder. The axial field is given by

$$E_z(r, \theta, z, t) = E_0 T_0(k_r r) \cos(k_z Z) e^{j\omega t}. \tag{3}$$

When $k_r r \gg 1$, the asymptotic form of the Bessel function is

$$J_\nu(k_r r) \simeq \sqrt{\frac{2}{\pi k_r r}} \cos\left(k_r r - \frac{\pi}{4}\right).$$

The rms electric field intensity at the radius a of the cylindrical tube is $E \simeq (\pi k_r a)^{-1/2} E_0$. The output power of the maser can be expressed in the form

$$P = c(1 - R)\frac{E^2}{8\pi} S, \qquad S = 2\pi a l,$$

where R is the power reflection coefficient of the interference coating and l is the length of the cylinder. Then the maximum field intensity at the center is given by

$$E_0^2 = \pi k_r a E^2 = \frac{8\pi^2 N}{c(1 - R)} \frac{P}{S}. \tag{4}$$

When the radial mode number N is large, the field intensity at $r = 0$ becomes large. For example,

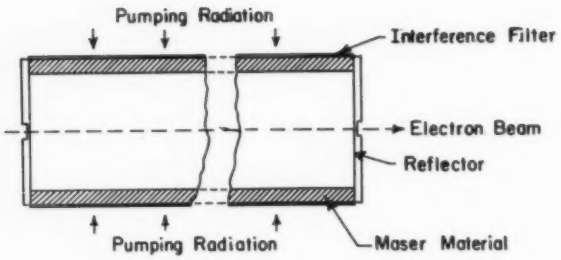

Fig. 1. Schematic diagram of an electron linear accelerator by optical maser.

for $N = 10^4$, $(1 - R) = 5 \times 10^{-3}$, and $P/S = 10$ kw/cm², the rms electric field is $E_0 = 1.2 \times 10^7$ volts/cm or 1.2 billion volts per meter.

The mode number N may be expressed in terms of the radial wavelength $\lambda_r = 2\pi/K_r$ by

$$N = \frac{k_r a}{\pi} = \frac{2a}{\lambda_r}.$$

Hence it is evident that the shorter the wavelength λ_r, the larger the field intensity at $r = 0$. However, in order to increase k_r at a constant frequency, k_z in Eq. (3) must be reduced, since there is a relation between k_r and k_z given by

$$k_0^2 = \left(\frac{2\pi}{\lambda_0}\right)^2 = k_r^2 + k_z^2, \tag{5}$$

where λ_0 is the free space wavelength.

III. Velocity Matching

In order that an electron may be accelerated by the high frequency field, the phase velocity of the wave must coincide with the velocity of the electron which is smaller than the light velocity. Several methods to match the phase velocity $v_p = \omega_0/k_z$ to the velocity of the electron v_e were considered. The value of $1 - \beta = 1 - v_e/c$ is 10^{-4} at 36 Mev and 10^{-5} at 109 Mev.

A. Dielectric Tube Resonator

In order to have $v_p < c$ in vacuo, k_r^2 must be negative, so that the axial field intensity is expressed by the function $I_0(k'r)$ where $k' = \sqrt{-k_r^2}$. Since this function increases predominantly by a factor $\exp(k'r)$, the diameter of the tube must be equivalent to one wavelength. Therefore, this method can only be used at lower frequencies in the conventional microwave range.

B. Loading by Dielectric Plates

When k_r is so small that $k_r \approx 10^{-2}\, k_z$, the phase velocity is larger than the light velocity by only a factor of the order of 10^{-4}. Then the wave and the electron can travel a path length of $L_1 \approx 10^3\, \lambda_0$ before exhibiting a large phase difference. Insertion of a dielectric sheet of thickness L_2 and of index of refraction n can restore this phase difference, when

$$\frac{L_1}{L_2} = (n - 1)\frac{c}{v_p - v_e} - n. \tag{6}$$

Substituting $n = 1.4$ and $(v_p - v_e)/c = 10^{-4}$ in Eq. (6) gives $L_1/L_2 = 4000$. Actually these dimensions should be modified when making holes in the sheets in order to allow electrons to pass. For $\lambda_0 \approx 10^{-4}$ cm, the spacing is $L_1 \approx 1$ mm and the thickness is $L_2 \approx 10^{-4}$ cm. Periodical loading by such fine sheets of dielectrics would not be practical, even if it could stand the intense radiation without absorption of optical energy.

C. Gas-Filled Cavity

High energy electrons are deflected only slightly by scattering. The probability of being deflected by an angle larger than θ is calculated as

$$\frac{\pi e^4 Z^2 N}{p^2 v_e^2} \cot^2 \frac{\theta}{2},$$

where N is the density of nuclei with charge $+ Ze$ and p is the momentum of the electron. For the electron of 300 Mev the probability of scattering by an angle larger than 10^{-4} radian is 2% per meter in hydrogen gas at 1.5 atm pressure, for which $n - 1 = 2 \times 10^{-4}$. Helium may be used instead of hydrogen if the frequency of the optical maser is fairly close to that of an absorption line of the hydrogen molecule. From Eq. (5) the condition for $v_p = v_e$ is found to be

$$1 - \beta = (n - 1) - \frac{1}{2}\left(\frac{\lambda_0}{\lambda_r}\right)^2. \tag{7}$$

The electron velocity changes with acceleration and it is very close to the light velocity at the high energy side of the accelerator. For $\beta = 1$, Eq. (7) gives $\lambda_r/\lambda_0 = k_0/k_r = 50$, when $n - 1 = 2 \times 10^{-4}$. This means that the diameter of the beam must be less than about $18\lambda_0$ in order that the field intensity in the beam be not smaller than 0.7 E_0. The ratio λ_r/λ_0 must be larger at a lower electron energy. The minimum injection energy for $1 - \beta = 2 \times 10^{-4}$ and $\lambda_r \gg \lambda_0$ is 25 Mev. A higher injection energy is preferable, because of less scattering and a lower value of $1 - \beta$. For injection at 36 Mev, $\lambda_r/\lambda_0 = k_0/k_r$ is 70, which is not significantly different from 50, a value at the end of the accelerator.

Changing the diameter of the cylinder or the pressure of the gas along its axis is not feasible. To keep the radial mode number unchanged while using a straight cylinder, insertion of a slightly tapered dielectric tube, as shown schematically in Fig. 2, is suggested. Since $k_r^2 > 0$ inside the tube, the diameter may be more than

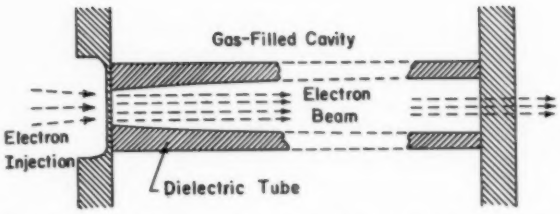

Fig. 2. Dielectric tube in a gas-filled cavity for velocity matching.

10 times the λ_r or about 1 mm. The necessary variation of the thickness of the inserted tube is only a small fraction of a millimeter. Therefore, it would be possible to obtain the TM_{0N} mode along its length by using a proper mode separation device. A proposed method is to place a periodically printed absorption (or dielectric) layer on the inner surface of the maser cylinder or on the inserted tube. Alternatively, some mode suppression diaphragms of a similar kind might be used. Such stripe-patterns might be produced by a photo-printing or photo-etching technique, or by electron beam machining.

IV. Conclusion

It has been shown above that an acceleration of 10^9 ev/meter could be obtained with a maser output of 10 kw/cm^2, if velocity matching and mode selection were achieved. However, with such a large high Q cavity there is likely to exist relaxation oscillation in the maser which must be suppressed.

Mode separation would be very difficult in a cavity especially when thermal expansion is taken into consideration. Beam loading and focusing have not been discussed here. The diameter of the accelerated beam is a fraction of the radial wavelength λ_r, and is about 10^{-3} cm when $\lambda_0 = 10^{-4}$ cm.

Finally, it may be said that the optical maser linac proposed here works on a reverse process of the Čerenkov effect in a gas. One should not be surprised to discover acceleration of electrons in a gas, since the number of collisions in the one-meter path length is roughly the same as that in a conventional synchrotron accelerator if the particle travels about 10^7 meters in a vacuum of about 10^{-5} mm Hg.

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Papers to appear in subsequent issues

Spectroscopy for Solid-State Optical Masers—*S. Sugano*
High Efficiency Optical Maser Parameters—*S. J. Sage*
Some Optical Maser Aspects of $CaF_2:U^{3+}$—*S. P. S. Porto and A. Yariv*
Mode Control in Ruby Optical Masers by Means of Elastic Deformation—*M. S. Lipsett and M. W. P. Strandberg*
Multiple-Pinhole Multiple-Beam Interferometric Observation of Flat Surfaces—*M. V. R. K. Murty*
High Speed Sequence Photography of a Ruby Laser—*E. S. Dayhoff and B. Kessler*
Threshold Condition of Masers for Higher Frequencies—*K. Shimoda*
Threshold and Stability of a Simplified Model Optical Maser—*E. J. Post*
Population Inversion in a Discharge in a Mixture of Two Gases—*N. G. Basov and O. N. Krokhin*
Overlapping Monoculars—An Ultra-Wide Field Viewing System—*M. Shenker, J. LaRussa, P. R. Yoder, and W. H. Scidmore*
Physical Optics of Coherent Radiation Systems—*J. E. Rosenthal*
Optical and Cross Relaxation Maser Level Populations by Partial Distribution—*W. A. Barker and J. D. Keating*
Thermal Imaging by Means of the Evaporograph—*G. W. McDaniel and D. Z. Robinson*
Inspecting Infrared Optical Materials and Systems by Means of the Evaporograph—*G. W. McDaniel and A. P. DiMattia*
Absorption Line Broadening in the Infrared—*D. E. Burch, E. B. Singleton, and D. Williams*

Optical Activities in Industry

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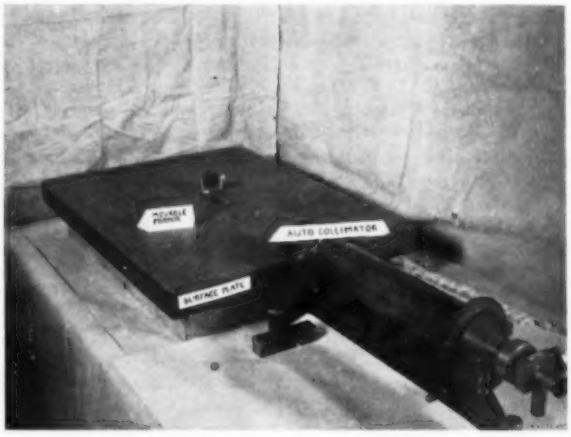

In some reports to come your scribe will attempt to show where Optics and Optical Instruments are further helping industry and science.

Suggestions and illustrations will be appreciated.

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During recent months, Electro-Optical Systems, Inc. of Pasadena, Calif., have been awarded two contracts for laser work. They have received $94,728 from the Air Force's Rome Air Development Center for development of advanced laser components for use in optical surveillance systems, and $24,545 from the National Aeronautics and Space Administration for a feasibility study of a laser beacon for daylight tracking and navigational purposes.

J. W. Fecker, Inc. announce . . . . that **Richard Walters** has moved from the Instrument Division of the American Optical Company in Buffalo to the Fecker Division in Pittsburgh to become Chief Lens Designer. . . . that **Robert Pilston** has joined the staff as a Senior Optical Engineer and **Ronald Humphreys** of the University of Southampton has come from England to work as a Junior Physicist. . . . that recent new contracts include a vacuum ultraviolet collimator and optical bench for NASA; this equipment will produce a collimated beam of ultraviolet light 0.96 m (38 in.) in diameter. Fecker will also be building two 61 cm (24 in.) missile tracking telescopes for the Air Force for ship-borne operation on the Atlantic Missile Range, and two 45.8 cm (18 in.) telescopes are being built for the French Government to be used in the Sahara Desert for observations of missile tests. . . . that the Company has moved from its location at 6592 Hamilton Avenue in Pittsburgh to a building with twice as much floor space at 4709 Baum Boulevard near the University of Pittsburgh.

Maurice F. Hasler, one of the founders of Applied Research Laboratories, Inc., has been elected Chairman of its Board of Directors.

Readers' attention is drawn to . . . . a useful reprint put out by **Missiles and Rockets** of the thirty-eight articles on optics published therein between April 1960 and April 1961. Information about this collection of reprints may be obtained from *Missiles and Rockets*, 1001 Vermont Avenue N.W., Washington 5, D.C. . . . the **Institute of Optics Newsletter** which makes *very* interesting reading . . . . Atomic Energy Commission research reports for sale through the Office of Technical Services, Business and Defense Services Administration, U.S. Department of Commerce, Washington 25, D.C. AEC-tr-4432 *Radiometry* April 1961, 389 pp. $4.50. AEC-tr-4471 *Optics in equipment for the utilization of solar energy* April 1959, 257 pp. $3.50. AEC-tr-4403 (Books 1 & 2) *Spectra of the rare earths* April 1961, 596 pp. $7.00 the set . . . . *International Practical Temperature Scale of 1948, Text Revision of 1960*, by Harold F. Stimson, National Bureau of Standards Monograph 37, issued September 8, 1961, 8 pp. $0.10, and *Tables of Spectral-Line Intensities, Part II, Arranged by Wavelengths*, by W. F. Meggers, C. H. Collins, and B. F. Scribner, National Bureau of Standards Monograph 32, issued October 2, 1961, 272 pp. $3.00. These first extensive tables of relative spectral-line intensities on a uniform energy scale present data over the wavelength range from 2000 to 9000 A for the 70 chemical elements most commonly encountered by spectrochemists—Order these two NBS Monographs from the Superintendent of Documents, Government Printing Office, Washington 25, D.C.

Relocation of Spectral Data Projects. The American Petroleum Institute Research Project 44 and the Manufacturing Chemists' Association Research Project were moved from Carnegie Institute of Technology to the A & M College of Texas last year. Both Projects issue standard reference spectrograms in each of five categories of spectroscopy: infrared, ultraviolet, Raman, mass, and nuclear magnetic resonance. The two Research Projects now constitute the Chemical Thermodynamic Properties Center in the Department of Chemistry of the Texas A & M. **Bruno J. Zwolinski,** Professor of Chemistry, is the Director of the Center and of the two Projects. **Alfred Danti,** Associate Professor, is the Assistant Director and is in charge of the Spectral Program. Spectra issued by the two Projects are contributed by responsible investigators. Contributions of spectra should be addressed to the Director or Assistant Director at the new address: *Chemical Thermodynamic Properties Center, Department of Chemistry, A & M College of Texas, College Station, Tex.*

The **Sixth National Infrared Information Symposium** was held at Patrick Air Force Base, just south of Cape Canaveral, Fla., on November 7, 8, and 9. Several Floridians were active in the planning and administration of this large and complicated meeting: **Dennis C. Marquis** of Pan American's Guided Missiles Range Division was a member of the program committee and was in charge of local arrangements. Assisting him were **Edward J. Madden** of the Directorate of Range Development, Air Force Missile Test Center, and **Charles Layne** of the local field office of the Barnes Engineering Company. An ex-Floridian **John N. Howard** was Chairman of the program committee. **Stanley S. Ballard,** OSA president-elect, of "nearby" Gainesville (150-miles—240 km!—distant) was also a member of the program committee. The logistics involved in holding a meeting on a military base, with several hundred attendees staying at motels stretching up and down Cocoa Beach, a distance of 10 miles, (16 km), were something new and terrifying for people accustomed to holding a scientific meeting within the orderly confines of a single headquarters hotel—but these do not deter **Mary Warga,** OSA Executive Secretary, who is hoping to arrange the OSA Spring 1963 meeting in Florida. OSA has only a few members in the State of Florida, and, with all the work going on in optics at the Cape, such a meeting would flush out many more.

Let there be (more and better) light! . . . Better lighting is in sight for football enthusiasts, and quartz iodine lamps instead of the usual incandescent lamps for field lighting are the answer, says the Illuminating Engineering Society. A trial installation of 64 specially designed lighting units set up recently at a football field at Brush High School, Lyndhurst, Ohio, which more than doubled the visibility on the playing field for spectators, was described at IES meeting by **Ronald L. Paugh, David A. Toenjes,** and **G. R. Baumgartner,** of General Electric's Large Lamp Department . . . . A new smaller fluorescent lamp which provides the same light as the conventional tubular fluorescent lamp was also described at this IES Conference. The panel type lamp, 30 cm square and only 3.8 cm deep, has the same high efficiency (60 lumens per watt), and long life (7500 hr) that the tubular fluorescent lamps have, according to **C. M. Cutler** and **W. C. Martyny** of the GE Lamp Division.

The following are some of the recent contracts awarded by the **Air Force Office of Scientific Research** that may interest our readers: Univ. of Washington, D. F. Eggers *Vibrational and Vibration-Rotational Spectroscopy*, $32,000; Indiana Univ. Fdn., E. J. Bair *Spectrometric Studies of Fast Reactions*, $62,542; Univ. of Mississippi, P. A. D. deMaine *Spectrophotometric and Non-Spectrophotometric Studies of Solutions*, $45,960; Columbia Univ., P. Kusch *Infrared and Optical Maser Research*, $39,889; Columbia Univ., R. Novick *Properties of Radioactive Atoms by Optical Orientation* $89,756; Univ. of Southern Calif., G. O. Young *Research in Computer Decision Processes* $15,100; Northwestern Univ., J. A. Hynek *Research in Balloon Astronomy* $149,500; Univ. of Michigan, G. Parravano *Sintering and Whisker Growth in Metal Oxides* $44,680; Univ. of Maryland, R. A. Ferrell and R. D. Myers *Fundamental Interactions in the Solid State* $235,175; and Mich. State Univ. of Agriculture and Applied Science, D. J. Montgomery *Interaction of Electromagnetic Radiation with the Crystal Lattice* $65,880.

continued p. 16

Recent Developments in Maser Devices and Materials

Hendrik J. Gerritsen

The properties of crystals used in solid state masers are discussed. A table is presented summarizing this information for present maser materials. It is pointed out that further material research needs to be done to improve the performance of masers and extend their frequency range.

I. Introduction

Since a number of good review articles on masers have been published (see e.g., refs. 1–6) this discussion will be limited to a survey of present-day materials for use in continuously-amplifying, paramagnetic solid state masers. The principle of the paramagnetic three-level maser was published in detail by Bloembergen.[2]

Most of the materials studied by paramagnetic resonance up to 1957 were water grown crystals and they were successfully tried in early masers.[7,8] It soon became apparent that the poor mechanical strength of these crystals and their tendency to absorb water are undesirable for maser applications and thus activity developed in the field of growing gemlike single crystals. A further stimulus to this development came recently from the advent of the solid state laser. It now seems clear that gems are superior to water soluble crystals for practical maser devices from the uhf to 70 kMc, despite the higher cost of producing good single crystals of the gems. Above 70 kMc special problems exist with respect to the available pump sources. It is not impossible that for these frequencies water-soluble crystals with the desired physical properties will be easier to find than the proper gemlike crystals.

II. The Three-Level Maser

In Fig. 1(a) the energy levels for a typical paramagnetic ion, situated in some host crystal and placed in a magnetic field, are shown. They are labeled E_1, E_2, and E_3 and will be referred to as E_i with $i = 1, 2,$ and 3. The length of the arrows represents the population, $n(E_i)$, in the energy state E_i. When no microwaves are present this population is given by Boltzmann statistics as follows:

$$n(E_i) = n(E_1) \exp [(E_1 - E_i)/kT]$$

and is indicated in Fig. 1(a) by the dotted line. If one applies saturating power between levels 1 and 3, one equalizes $n(E_1)$ and $n(E_3)$ and the situation sketched in Fig. 1(b) will result. Since the population of spins in level 2 is larger than that in level 1, amplification will occur for a frequency $(E_2 - E_1)/h$, the signal frequency. We will refer to the frequency $(E_3 - E_2)/h$ as the idler frequency, and $(E_3 - E_1)/h$ as the pump frequency.

III. Operating Characteristics of Masers

An enumeration of maser characteristics follows which will be related to maser materials in Section IV.

A. Signal Frequency

Maser devices have been built for signal frequencies ranging from uhf up to 70 kMc.

B. Bandwidth

Actually two sorts of bandwidths have to be distinguished—the instantaneous bandwidth and the tunable bandwidth.

The tunable bandwidth is defined as the frequency band over which the maser can be tuned while having a gain of more than half the maximum gain.

The instantaneous bandwidth is the frequency band over which the maser, set at a fixed signal frequency, amplifies.

The instantaneous bandwidth will be discussed first. Its value depends upon the material used and on the mode of operation. The interaction between paramagnetic ions and an electromagnetic wave traveling with light velocity is too small to use in practical devices, so that it is necessary to increase this interaction. The material can be placed in a structure which slows the electromagnetic waves down or in a resonant structure, such as a microwave cavity. In the first case one defines slowing as the ratio between the velocity of light and the velocity of propagation of microwaves in the paramagnetic material.

The author is now at the Chalmers University of Technology, Gothenburg, Sweden.

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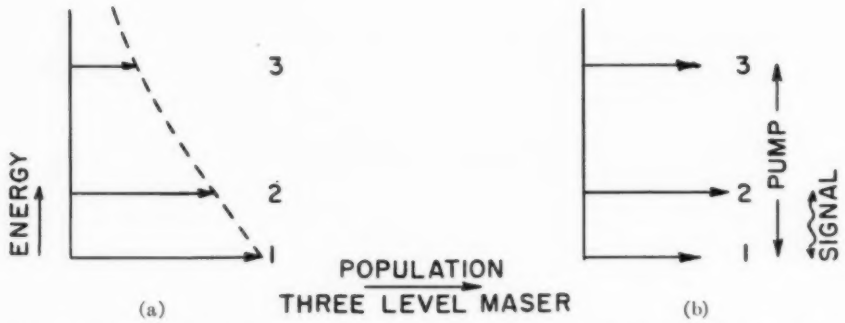

Fig. 1. (a) Population, $n(E_i)$, when no microwave power is applied follows Boltzmann statistics: $n(E_i) = n(E_1) \exp[(E_1 - E_i)/kT]$. (b) Population under the influence of large microwave power of frequency $(E_3 - E_1)/h$. $n(E_1) = n(E_2)$ and amplification of frequency $(E_2 - E_1)/h$ is now possible.

There are two ways of obtaining slowing: by making use of periodic metal structures such as comb, karp, helix, and meanderline structures,[9] or by using dielectric slowing.[10] In the latter case the slowing is simply $\sqrt{\epsilon}$, where ϵ is the dielectric constant of the material.

An early successful traveling-wave maser, using ruby in a comb structure,[9] had an instantaneous bandwidth of 25 Mc, a power gain of 23 db, the signal frequency was 5.8 kMc, and the operating temperature 1.5°K. Recently, a ruby traveling-wave maser has been reported[11] which used an inhomogeneous magnetic field to widen the response of the paramagnetic material. This structure had a 100 Mc bandwidth and gave 11 db net gain at 2.28 kMc. The ruby rod was 16.5 cm long and kept at 1.8°K.

The instantaneous bandwidth values for several representative cavity masers are shown in Fig. 2 at a gain of 20 db. Traveling-wave masers seem to offer larger bandwidths than cavity masers, but cavity masers are easier to construct than traveling-wave masers, especially at high frequencies. The traveling-wave masers reported in the literature operate below 10 kMc, with the exception of one based on dielectric slowing only.[10]

The tunable bandwidths of traveling-wave masers using metal structures for slowing are rather limited since the slowing factor is very frequency sensitive at high values of slowing. A tunable bandwidth of 350 Mc was reported in the Bell Telephone Laboratories traveling-wave maser.

Cavity masers are rather well tunable if one makes both signal and pump resonance independently tunable. A maser with a tunable bandwidth of 1 kMc is described in the literature.[12] The traveling-wave maser which used dielectric slowing could be tuned over 4 kMc by changing only the magnetic field and, over 15 kMc, by changing pump frequency also. This can be done easily since dielectric slowing is frequency independent up to infrared frequencies.

C. Gain

In both cavity and traveling-wave masers one can trade gain and bandwidth against each other. In general one tries to obtain stable gains between 20 and 30 db, so that one overcomes all other noise sources and then accepts the best possible bandwidth. In cavity masers one obtains this trading by varying the coupling between waveguide and cavity.

If one denotes gain by G and instantaneous bandwidth by B, one has in cavity masers the relation: $G^{1/2}B$ is constant, where the constant depends upon the material used. In traveling-wave masers one makes the maser as long as practically possible and then widens the paramagnetic line width by using an inhomogeneous magnetic field, thereby increasing the instantaneous bandwidth with consequent reduction in gain. Another aspect of importance is gain stability. To protect the maser against large gain fluctuation when the load resistance varies, it is essential to build some kind of isolation or unidirectionality into the system.

D. Signal Saturation and Recovery Time

At a certain level of signal power, the signal becomes strong enough to saturate the populations $n(E_2)$ and $n(E_1)$.

This results in a reduction of spins available for giving up energy and thus in a reduction of gain. The level at which this occurs depends, among others, upon the spin lattice relaxation time defined below. It is typically of the order of 1 μw. This in itself would not be of great consequence, since the maser is only important for the detection of signals many orders of magnitude smaller. However, if one uses the maser in a radar system, some of the power of the outgoing pulse will enter the receiver. This can result in saturation at the signal frequency, and once the maser is saturated it will stay saturated for some time. This time is called the spin lattice relaxation time and is a material

constant. For ruby masers it is undesirably long, of the order of 100 msec, and for that reason one needs a device in front of the maser to protect it against the leaking in of transmitter power.

Some materials have such short spin lattice relaxation times that they do not need protection. The disadvantage of a protective switch is mainly that it tends to add noise to the maser and of course also increases the complexity of the system somewhat.

E. Pump Frequency

The maser has to be pumped with microwave power. In the three-level maser the pump power has to be at a frequency higher than that of the signal. Practically all masers do operate this way, with the exception of those described in refs. 13 and 14.

F. Pump Power

The power necessary to pump a maser is generally speaking of the order of 100 mw or less. It is important to apply so much pump power that the 1–3 transition is thoroughly saturated, because in that case fluctuations in the pump power are unimportant. This is one factor that makes masers superior to parametric amplifiers, where the feature of pump saturation does not exist.

The highest pump frequency at which sufficient power is available is at present about 150 kMc. For that reason the highest signal frequency at which amplification has been obtained is 72 kMc.[15] It is therefore clear that to increase the signal frequency one has to use methods of lower frequency pumping, as will be discussed later.

G. Temperature

Most masers operate at liquid helium temperatures, that is, between 4 2°K and 1.2°K.

It has been demonstrated that a ruby maser can be operated at a temperature as high as 195°K,[16] though with small gain. At liquid air the performance is better, but still one pays a rather heavy penalty in bandwidth compared to the bandwidth obtainable at liquid helium for the same gain. There may be applications where operation at a temperature above that of liquid helium is important. If one uses cooling liquids, a given volume of liquid helium lasts a shorter time than the same volume of liquid hydrogen which itself lasts for a shorter time than the same volume of liquid

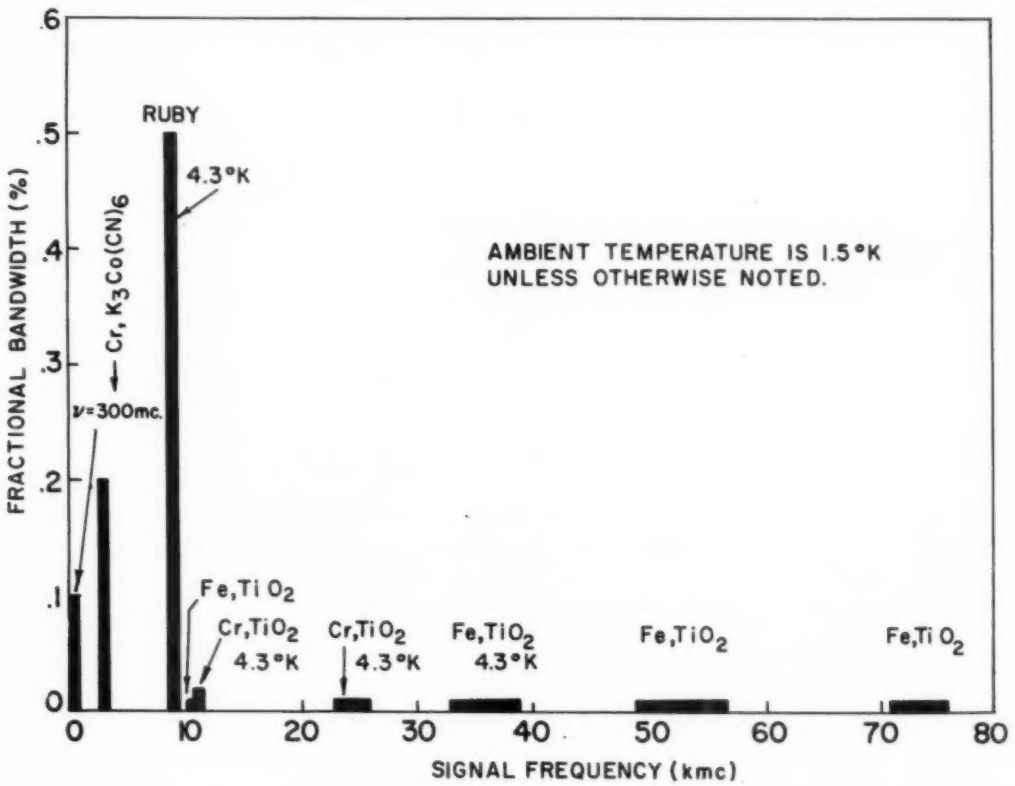

Fig. 2. The fractional bandwidth at 20 db gain of some cavity masers.

nitrogen. Also, in space applications one may desire to cool by radiating the heat away rather than by using a cooling liquid. In that case it requires about 200 times less radiating area to cool a maser to 15°K than to 4°K.

H. Noise Temperature

The noise temperature of helium-cooled masers is very small, typically a few degrees. For that reason the important noise contributions in a maser amplifier originate in other parts of the system. In order to prevent thermal radiation at the output from entering the maser a good isolator is needed between the maser and the output or, alternatively, a built-in gain unidirectionality is required.

IV. Materials and Maser Characteristics

In this section a discussion will be given of how the properties of materials influence maser performance and what one requires from new materials in order to realize certain maser goals.

In the table an enumeration of material constants is given for a group of doped crystals. It should be pointed out that the materials are listed in chronological sequence, which does not necessarily represent one of increasing figure of merit. A single figure of merit does not exist for maser materials, and some properties exclude others. For example, a short spin lattice relaxation time leads to a maser which has a favorably short signal recovery time, but on the other hand requires a large amount of pump power. Such a material is useful in low-frequency radar application but not so useful for high-frequency operation, where presently available pump powers are small. In addition some materials are listed which seem promising but have not actually yet been tried in masers. A few other materials that may prove promising are not included, simply because even less is known about their maser properties.

It should be possible, with sufficient theoretical knowledge, to choose certain host crystals doped with certain ions in order to obtain the properties necessary for a desired maser application. Unfortunately crystal field theory is still in too crude a form to be of much help and the choice is thus based upon availability of crystals, analogy, and chance.

Some general information is available from early paramagnetic resonance work[17,18] about ions that have energy level splittings such as those shown in Fig. 1 and thus may be suitable for masers. In addition the references include a discussion on the theoretical methods used to calculate energy level diagrams from a few constants of the material. A discussion of the important maser material parameters will now be given.

A. Zero Field Splitting

Even in the absence of a magnetic field a splitting of energy levels occurs—the zero field splitting. Its value determines to a great extent the frequency behavior and gain behavior in a maser. Figure 3 shows the energy levels for a trivalent chromium ion in two different crystal lattices as a function of magnetic field strength. The zero field splitting in the case of chromium in rutile is about four times as large as in the case of chromium in corundum. This means that the energy levels in ruby vary linearly with field above about 5 kgauss while for chromium in rutile, fields of about 20 kgauss are required before this would occur. In the region where energy is nearly a linear function of field, the wave functions describing these energies are, rather, purely those of a free spin, for which only transitions to

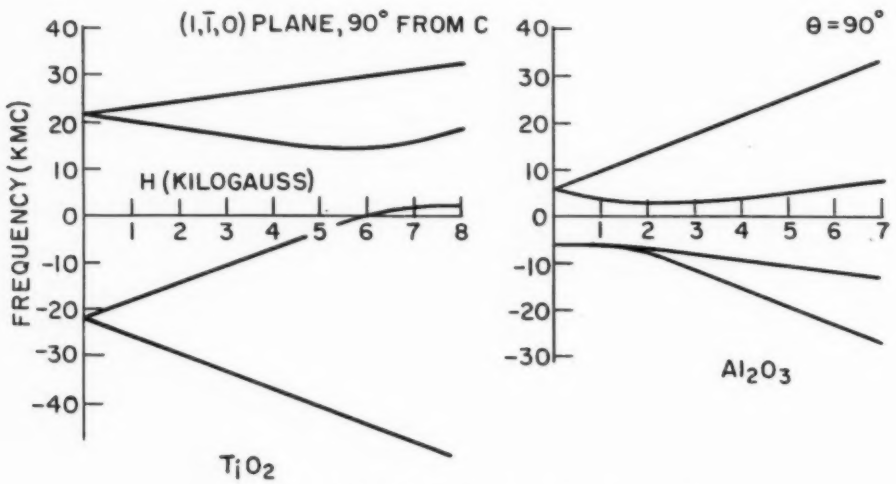

Fig. 3. Energy levels of chromium in two maser materials.

the neighboring energy levels are allowed. As a consequence it becomes very hard to pump between levels 1 and 3, and much pump power is needed which is mainly wasted as heat in the surrounding microwave structure. As a crude rule of thumb, one can say that the highest pump frequency one can use is of the order of twice the zero field splitting. This is because above that frequency the energy versus magnetic field curves start rapidly to approach straight lines.

The way in which the range of signal frequencies at which maser amplification can be obtained depends upon the zero field splitting will now be discussed. Since the maser is based on inversion, one can show from the basic equation[2] that when all spin lattice relaxation times are equal, the highest signal frequency at which amplification is possible is slightly less than half the pump frequency in a three-level maser. (This statement does not hold for some of the special pumping schemes to be discussed later.) Since the highest pump frequency is about twice the zero field splitting, the highest signal frequency in a three-level maser is about equal to the zero field splitting. In the direction of low signal frequencies the limit is the line width of the material and is of the order of 100 Mc. In that case one can pump at a frequency about equal to the zero field splitting.

Some ions have more than one zero field splitting, as is shown in the table. In that case the highest signal frequency obtainable is of the order of the entire zero field splitting.

Theory and experiment point out that ions which give rise to the kind of diagrams described in Figs. 1 and 3 are Cr^{3+}, Fe^{3+}, Gd^{3+}, and Ni^{2+}. For applications of very high frequency some trivalent rare earth ions may have the proper, large, zero field splittings.[19] These are Ce^{3+}, Nd^{3+}, Sm^{3+}, Gd^{3+}, and Dy^{3+} in suitable host crystals.

The zero field splitting also has bearing on the gain and thus on the bandwidth, since the latter two are not independent. It can be shown easily[2] that the gain is proportional to the difference between populations $n(E_2)$ and $n(E_1)$, which is positive in a maser, and increases with increasing difference between pump frequency and signal frequency.

When amplification at a given signal frequency is required, it is generally desirable to choose a material with a large zero field splitting, so that the pump frequency is high, as high as is compatible with pump powers.

B. Dielectric Constant

A high dielectric constant has an important influence on the structures to be used in a maser. In Fig. 4 a traveling-wave maser is shown in which the slowing is purely dielectric.

Although the maser was only 1.9 cm long, a power

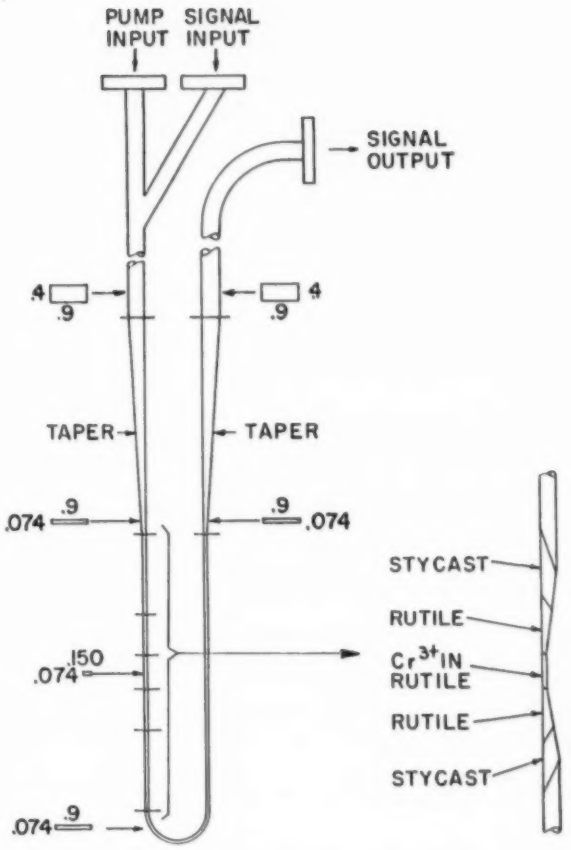

Fig. 4. A traveling-wave maser with no external slowing structure.

gain of 3.4 db was obtained at 4.2°K and 6 db at 1.4°K, in agreement with calculations. The instantaneous bandwidth was 20 Mc and tunable bandwidth was 15 kMc. In addition to enormous tunability, this structure is quite small even at X-band. This makes it attractive to use permanent magnets inside the dewar to obtain the magnetic fields needed. In addition the small cross section relieves the pump power requirements considerably.

Cavity masers using a material with a high dielectric constant, such as rutile, are also very different from the conventional type. By placing a rutile crystal in a waveguide and terminating the waveguide with a tunable short, very sharp cavity-like resonances are observed originating in the dielectric material. This observation was used in the first rutile masers.[20]

A theoretical treatment of this effect has been given by Okaya,[21] and experimentally it was found that practically all possible resonance modes are excited and many of them can be matched by the use of the plunger.

C. Spin Lattice Relaxation Tmie

The constant expressing the coupling between paramagnetic ions and lattice is called the spin lattice relaxation time and is the time it takes a group of paramagnetic ions that has been saturated with a short microwave pulse to recover via heat exchange with the lattice. This time is strongly temperature dependent and is given in the table at 4.2°K. There is much variation in the data obtained by different authors and the values given are averages.

The relation between spin lattice relaxation time and saturation and recovery in masers has already been pointed out in the previous section.

D. Idler Doping

The three-level masers considered so far used one kind of paramagnetic ion with a long to moderately long spin lattice relaxation time. It is possible to dope the crystal with another ion—the idler doping ion—in addition to the maser ion. This ion must have a very short spin lattice relaxation time. If this ion has a transition that coincides with the idler transition, $(E_3 - E_2)/h$, of the maser ion, the result will be that the spin lattice relaxation at the idler frequency becomes very fast. One effect of this is that signal saturation occurs now at much higher signal levels since spins that have given off energy and are in level 2 do not accumulate there, but are rapidly relaxed to level 1. For the same reason the pulse recovery time is shortened. The other effect is one of enhanced difference in population between levels 2 and 1 and thus of increased gain. This can be derived from the equation in ref. 2.

A good idler doping ion has very strong coupling with the lattice; useful ions are Ce^{3+}, Er^{3+}, Co^{2+}, and Ti^{3+} and in some crystal fields, Fe^{3+}. The reason for the short spin lattice relaxation time of those ions is the presence of an orbital level not very high in energy above the ground state. The additional requirement of coincidence between maser ion levels and idler ion levels should be mentioned as a disadvantage of idler doping since it makes the maser much less tunable.

V. High Frequency Masers

Since the highest frequency at which pump power is available is at present about 150 kMc, it requires special schemes to obtain maser amplifiers above this frequency. Figure 5 shows three cases in which signal amplification can be obtained in a four-level scheme at frequencies above the pump frequency. The first two schemes make use of idler doping. The transition of the idler doping ion is denoted by a heavy arrow in the drawing. The first scheme was suggested by Makhov[22] and its realization described by Minkowski,[13] in potassium cobalti cyanide in which chromium served as the maser ion and iron as the idler doping ion. The pump frequency was at 5.71 kMc and amplification was obtained at 9.63 kMc. The second scheme is very similar in principle to the first one, but has not yet been used in masers with low frequency pumping.

The third scheme is based on harmonic pumping. In that case no idler doping ion is needed. The only requirement is that a harmonic relationship exists between the frequency at which a large amount of saturating power is applied and the real pump frequency, $(E_4 - E_1)/h$. Experimental evidence of the existence of harmonic coupling was obtained by several authors.[23] This scheme was suggested in relation to masers by Bloembergen *et al.*[24] and reported by Arams[14] in ruby where the pump frequency was at 9.59 kMc and the signal frequency at 10.59 kMc.

Figure 5(c) shows the case where the splitting between one pair of levels is twice the splitting between another pair of levels. There exists a spin reaction that involves no energy transfer to the lattice. In this reaction one spin makes a transition upwards

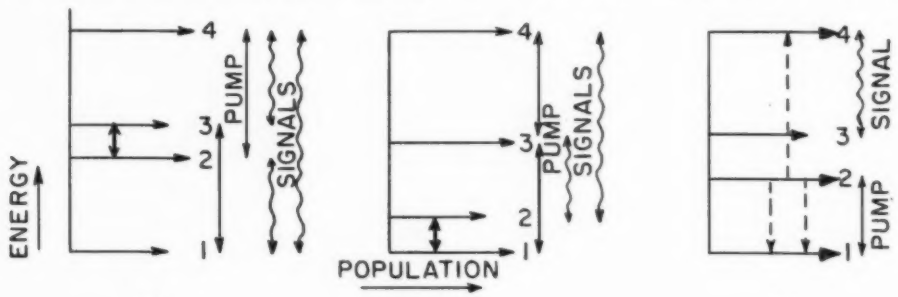

Fig. 5. (a) Push-pull scheme: $E_3 - E_1 = E_2 - E_4$. When $E_3 - E_2$ is made to coincide with the energy separation of another ion—the idler doping ion—which has a very short spin lattice relaxation time, amplification is possible at a frequency higher than the pump frequency. (b) Push-push scheme: $E_3 - E_1 = E_4 - E_3$. Now the idler doping is made to occur between levels 1 and 2 and again the signal frequency is higher than the pump frequency. (c) Harmonic pumping: No idler ion is necessary here. $E_2 - E_1 = {}^1/_2(E_4 - E_2)$. A process can take place in which two spins jump down from level 2 to 1 while simultaneously one spin jumps up from level 2 to level 4. Thus, $n(E_1) = n(E_2) = n(E_4)$.

Properties of Maser Materials

Host crystal → / Physical property ↓	Lanthanum ethyl sulphate $La(C_2H_5SO_4)_3 \cdot 9H_2O$	Potassium cobalti cyanide $K_3Co(CN)_6$	Corundum Al_2O_3	Beryl $Be_3Al_2Si_6O_{18}$	Rutile TiO_2	Cassiterite SnO_2	Calcium tungstate $CaWO_4$	Yttrium oxide Y_2O_3
Maser ions	Gadolineum^{3+}	Chromium^{3+}	Chromium, iron^{3+}	Chromium^{3+}	Chromium, iron^{3+}	Iron^{3+}	Gadolineum^{3+}	Chromium^{3+}
Idler doping ions used	Cerium^{3+}	Iron^{3+}	None		None		Erbium^{3+}	
Mechanical strength	Poor	Rather poor	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Crystal size available	Large	Large	Very large	Small	Large	Small	Large	Large
Number of nonequivalent ions	1	2	1	1	2	2	1	4
Δ_3		Cr^{3+}: 5.1 kMc	Cr^{3+}: 11.4 kMc	Cr^{3+}: 53.7 kMc	Cr^{3+}: 43.3 kMc	Fe^{3+}: 92 kMc, 76		Cr^{3+}: 72.2 kMc
Zero field splittings	Gd^{3+}: 3.39 kMc, 2.50, 1.40						Gd^{3+}: 17.9 kMc, 10.4, 4.6	
Δ_2								
Δ_1			Fe^{3+}: 19.2, 11.8	Fe^{3+}: 1.8, 1.7	Fe^{3+}: 81.3, 43.3			
Highest signal frequency operated so far	9 kMc	9 kMc	11 kMc: Cr, Fe	10 kMc	Cr: 24 kMc Fe: 72 kMc	Not	1.5 kMc	Not
Dielectric constant at 4.2°K		5	9–11	6–7	130–260	24(300°K)		
Loss tangent at 4.2°K			$<7 \times 10^{-4}$		2×10^{-5}			
Spin lattice relaxation at 4.2°K for maser dopings (≈0.1 to 0.05%)	0.01 msec Gd-Ce	50—5 msec Cr ↓ CW ↓ pulsed	30 msec Cr 3 msec Fe		2.5 msec Cr		0.02 msec Gd-Er	10 msec
Low frequency pumping:								
Pump frequency		5.71 kMc	9.59 kMc					
Signal frequency		9.63	10.59					
Method		Push-pull idler doped	Harmonic pumping					
Highest temperature operated	4.2°K	4.2°K	200°K	4.2°K	15°K		4.2°K	

from level 2 to level 4 while two spins simultaneously make a transition downwards from level 2 to level 1, in this way conserving energy. If one pumps levels 1 and 2 one can in this way simultaneously saturate levels 2 and 4. This will occur if the time involved for the reaction is shorter than the spin lattice relaxation time between levels 2 and 4. This makes harmonic pumping specially favorable in crystals with long spin lattice relaxation times and one of the most favorable cases is certainly ruby. Sufficient results for constructing a practical device have so far been reported only up to the second harmonic, although harmonic effects were observed up to the 5th harmonic and higher.[23c]

So far none of these schemes has been used to push the limit of signal frequencies upwards. The brute force method of the three-level maser, pumped at 150 kMc and amplifying at 72 kMc in a field of 20 kgauss was used by Foner *et al.*[15] with iron doped rutile. Carter[25] employed a push-pull scheme without idler doping, also using iron doped rutile, and reported amplification at 57 kMc, while pumping at 78 kMc in a field of 6 kgauss. It seems likely that the search for proper idler doping ions in a suitable crystal or for harmonic pumping, with carefully controlled doping of the maser ion, will ultimately result in amplifiers above 150 kMc.

If the new limit of pump frequency were set at 150 kMc, one could still hope, by using second harmonic coupling in combination with idler doping, to obtain signal frequencies about three times this value, or about 500 kMc. The magnetic fields necessary for such an operation would be of the order of 50 kgauss and could be supplied with the new superconducting alloys. It is clear that in order to obtain these signal frequencies materials research is essential. In order to improve on this figure one would probably have to wait for further development in pump power sources.

With the appearance of lasers, it seems likely that the principle of pumping with incoherent light and obtaining amplification or oscillation at a lower frequency can be extended downwards. One of the difficulties here is that at high frequency the noise temperature of the maser increases, so that the lowest noise temperature theoretically possible, caused by spontaneous emission, of a maser amplifier operating at 1000 kMc would be 50°K.

A kind of amplifier in which this problem does not exist is the quantum counter.[26,27] This device merely detects quanta, and cannot be used as an oscillator.

It seems evident that increased materials research will result in a further increase in signal frequencies of masers, a decrease in signal frequencies of lasers, and the advent of quantum counters, thus bridging the gap in the infrared frequencies, for which, at present, no satisfactory methods of detection exist.

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The Interference between Beams from the Opposite Ends of a Ruby Optical Maser

P. Kisliuk and D. J. Walsh

A pulsed ruby optical maser has been constructed which allows the beams from opposite ends to be superimposed. Interference fringes have been observed which can be interpreted to show that the coherence predicted by theory is, in fact, obtained, and also that the relative spatial distribution of the light over the ruby face is essentially constant even though the light is emitted in short bursts.

According to theory the internal light beam in an optical maser oscillator of the usual cylindrical geometry consists of nearly plane standing waves.[1,2] The traveling waves, of which these standing waves are composed, should therefore have a fixed difference of phase between any two points, and, in particular, the superposition of the beams emerging from opposite ends should exhibit interference. Because the light is also highly monochromatic, observation of these fringes is expected to be relatively simple. Fringes due to such a superposition have, in fact, been observed in the experiments to be described.

The maser was constructed to permit the use of external adjustable mirrors rather than the usual mirrors of metal evaporated directly onto the crystal face. It has been used successfully in a number of experiments to be reported elsewhere.[3,4] Fringes have been observed with two arrangements which are optically almost equivalent and are illustrated in Fig. 1. Fringes which have been obtained with these arrangements are shown in Figs. 2 and 3.

That the light from a ruby maser consists of nearly plane waves is demonstrated by their small angular spread—about $^1/_5$ degree in the present experiments—and by the experiment of Nelson and Collins[5] involving the fringes obtained by the interference between the light beams arising from two slits on a single face of the ruby. By contrast, the present experiment shows that the phase difference between the light beams emerging from opposite ends is very nearly constant. This result is compared with the situation met in more conventional light sources. See Fig. 4.

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While the condition discussed above is necessary for the observation of fringes, it is not sufficient. The light output of ruby optical masers at the temperature of these experiments consists of short bursts each lasting about one microsecond.[6] There is no a priori reason to be confident that the spatial distribution of the light across the ruby face is the same for each "spike." The possibility of such variation appears greater because of the complexity of this light distribution, which is illustrated in Fig. 5. The observation of fringes shows that this distribution must be nearly the same for all of the "spikes" during one discharge of the flash tube. The manner in which the fringes would be obscured if this were not so is illustrated in Fig. 6. The most closely spaced fringes observed were $\sim$0.008 cm apart which shows that the center of gravity of the light did not spend an appreciable fraction of the time displaced by more than 0.004 cm from its average position. Thus it was fixed within 10^{-2} of the diameter of the ruby face and within 0.03 of the diameter of the bright spot shown in Fig. 5.

Nevertheless, the fringes are not perfectly regular. This is consistent with the result of Nelson and Collins[5] that the fringes they observe from separate illuminated portions of the ruby face are somewhat displaced. Assuming that the irregularities observed in the present experiment are due to characteristics of the maser beam itself rather than to imperfections of the external optical system, an explanation of how this might occur is illustrated in Fig. 7.

A point to note, in experiments such as this, is the effect of polarization of the maser light. The ruby rod used in this experiment had its axis perpendicular to the *C*-axis of the crystal. Under this condition the maser light is nearly 100% polarized with the **E**-vector perpendicular to the *C*-axis.[7] Consider, in the arrange-

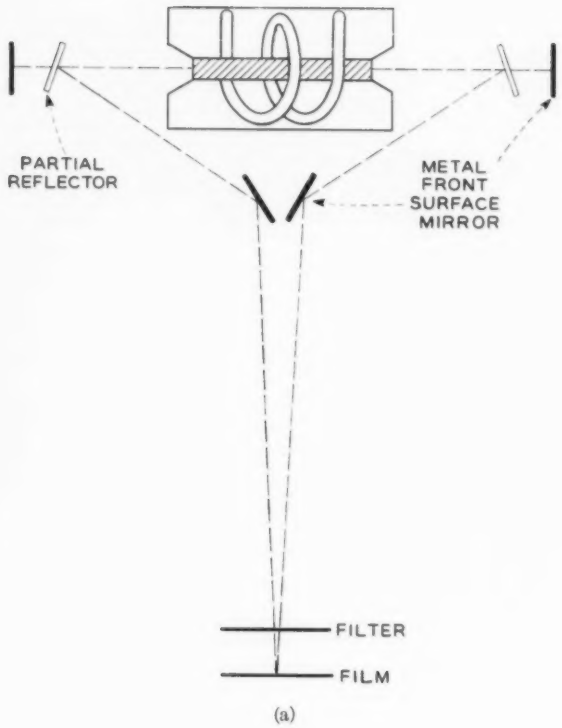
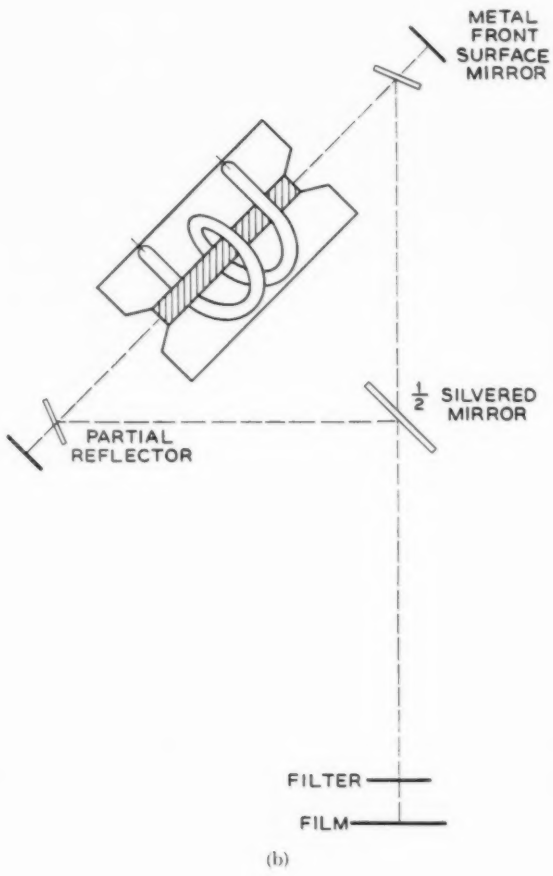


Fig. 1. The experimental arrangements. In the case of arrangement (b) fringes were not observed when the two beams were made as nearly collinear as possible, but only when two of the mirrors were displaced so as to combine the beams at a slight angle.



ment of Fig. 1(a), the case in which the perpendiculars to all of the mirrors and the axis of the ruby rod are all in the horizontal plane. Let the C-axis of the ruby be 45° from the vertical. Then, if the beam emerging to the right has its plane of polarization 45° clockwise from the vertical, that emerging to the left will have its plane of polarization 45° counterclockwise from the vertical, and when these beams are superimposed the polarizations will be at right angles, resulting in the complete absence of fringes. Some of our early difficulties in observing these fringes are attributed in retrospect to having the C-axis too close to this angle. If it is nearly vertical or horizontal, or if a polarizer is placed in front of the film, this difficulty is avoided. It does not arise at all in the arrangement of Fig. 1(b).

In summary, one of the unique properties of the optical maser as a source of light has been experimentally demonstrated. This observation has the further consequence of showing the constancy in time of the relative spatial distribution of intensity in the plane of the wave front.

This presentation has benefited from helpful comments by C. G. B. Garrett and J. S. Courtney-Pratt.

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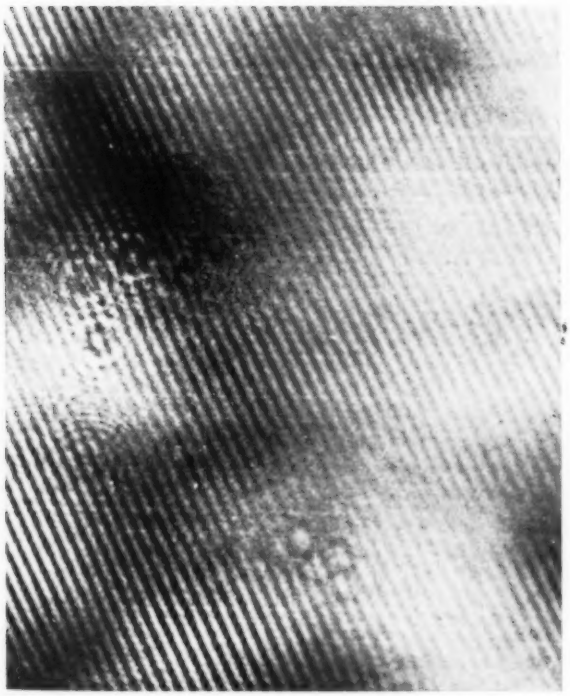
(a)

(b)



(c)

Fig. 2. Demonstration of interference fringes obtained with the arrangement of Fig. 1(a). (a)—Beam from left-hand side only. Diffuse lines are probably due to interference between beams from the front and back surfaces of the partial reflectors (glass optical flats with antireflection coating on rear surface). Small concentric circles are from the interference of spherical waves from dust particles on the filter with the incident plane waves. These serve, incidentally, as markers to identify equivalent portions of the film. (b)—Beam from right-hand side only. (c)—Beams from both sides superimposed to show interference fringes. Actual spacing on film is 0.012 cm which agrees with that expected within experimental error.

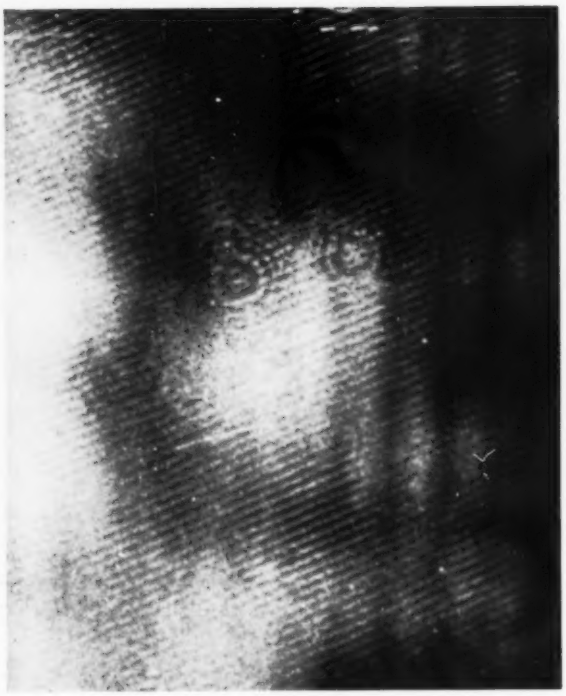


Fig. 3. Interference fringes obtained with the arrangement of Fig. 1(b)

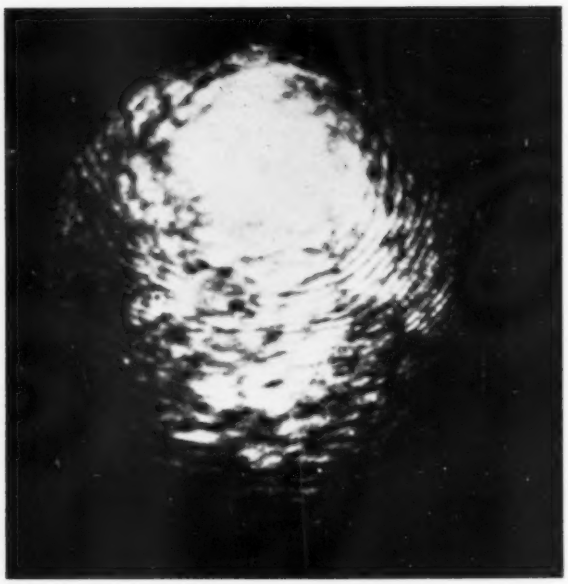


Fig. 5. A photograph of one end of the ruby exposed for one discharge of the flash tube under conditions where maser action takes place. (Actual diameter of ruby face, 0.5 cm.)

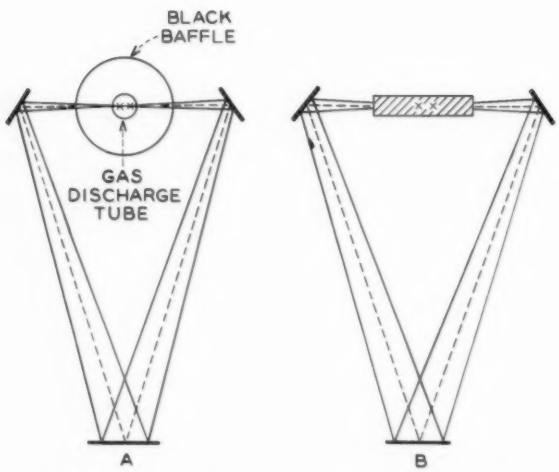


Fig. 4. A. Schematic diagram of conventional light source with baffles to limit beam to same solid angle as the maser beam. ×'s represent individual atoms emitting light of independent phase, resulting in superposition of many fringe systems and, therefore, no observable fringes. B. Excited atoms in maser are stimulated to emit light in such phase as to enhance standing waves in Fabry-Perot modes of the resonator, resulting in coherence of extracted beam and the presence of observable fringes.

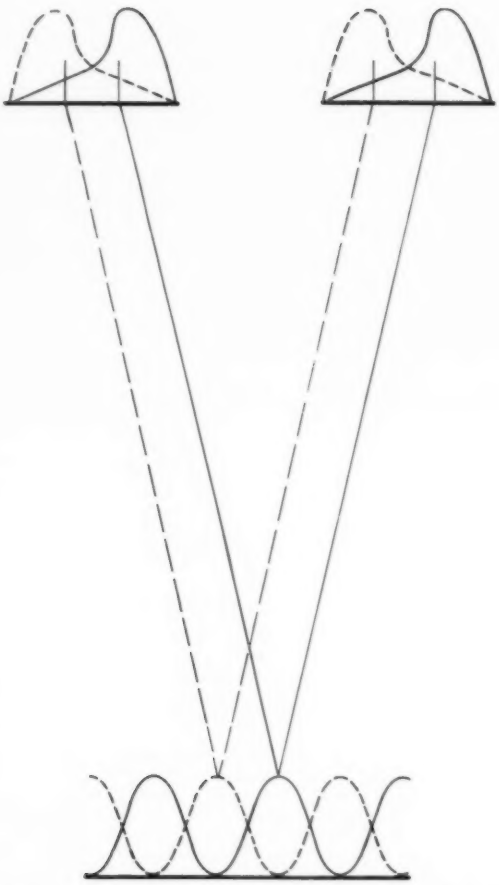


Fig. 6. Solid lines show hypothetical variation of intensity across the diameter of the ruby face and the corresponding fringes. Dotted lines show a possible situation at a later time which, if each contributed equally, would obscure the solid fringes.

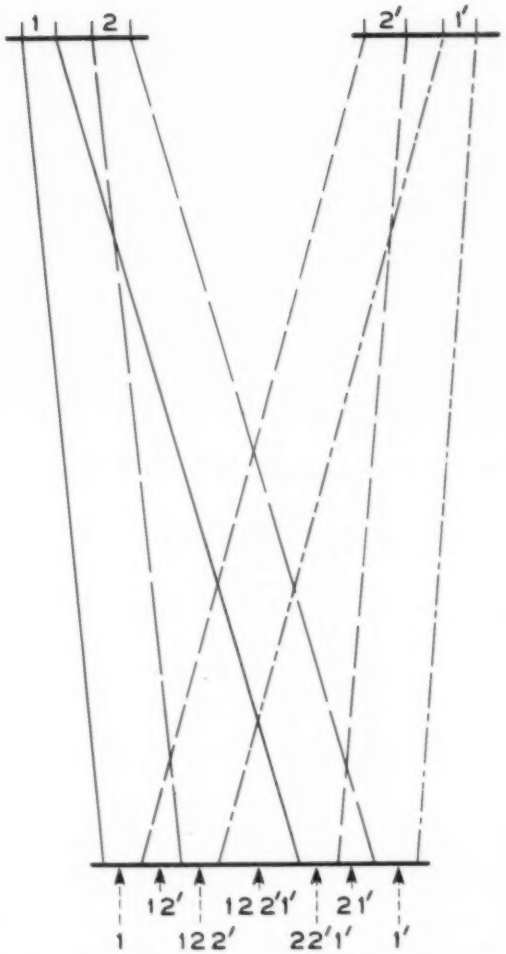


Fig. 7. Diagram to show a plausible explanation of irregularities in the fringes. If there is a difference in phase at the ruby face between beams 1 and 2 (and, therefore, between beams 1′ and 2′), the pattern will be clear and regular only where the film is exposed to but one beam from each end. Irregularities will occur in regions exposed to both 1 and 2 or both 1′ and 2′, since the relative portions of each will vary with position.

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Photomixing Experiments with a Ruby Optical Maser and a Traveling-Wave Microwave Phototube

B. J. McMurtry and A. E. Siegman

A standard oxide-cathode S-band traveling-wave tube has been used as an improvised microwave phototube to study the coherent light output from a ruby optical maser (laser). The laser's output consists of simultaneous, discrete optical components separated by the mode interval of 600 Mc/s between axial modes in the 12.5 cm laser rod. These components heterodyne in the TWT cathode to produce easily observed microwave outputs within the TWT bandwidth, corresponding to photobeats between third- through seventh-nearest-neighbor axial modes. This technique is a powerful tool for the study of optical masers, and also has important implications for communications via microwave-modulated light.

Introduction

This paper reports the observation of microwave signals produced by photomixing[1] of near-neighbor axial mode components in the output spectrum of a ruby optical maser. The observations were made by focusing the laser's output onto the oxide cathode of a standard traveling-wave tube (TWT) with a nominal 2000–4000 Mc/s passband. Mixing (heterodyning) between the simultaneous, discrete optical frequencies in the laser's output occurs in the TWT cathode, producing an initial microwave amplitude modulation of the beam current. This modulation is amplified by the usual traveling-wave interaction in the helix section of the TWT, producing easily observable microwave signals in the TWT output. Adjacent axial modes, i.e., optical resonances which differ by one in the number of axial nodes along the laser rod, are spaced by $\sim$ 602 Mc/s in our laser. Within the TWT bandwidth, we observe discrete and independent signals at 1800, 2400, 3000, 3600, and 4200 Mc/s, corresponding to the photo-beats between the third through the seventh nearest neighbors in the laser mode spectrum.

Experimental Arrangement

Our laser employs a 14 cm long by 3.2 mm diameter Linde pink ruby rod in an elliptical pump cylinder similar to the Raytheon design.[2] The rod is several years old, and of uncertain concentration and homogeneity. The optically flat ends, parallelism not known, are heavily silvered, with an 0.015 mm slit along a diameter of one end. The EG&G FX-1 flashlamp produces laser action at a few hundred joules input when the system is cooled by nitrogen vapor; the measurements reported here were made at inputs from 1.1 to 2 times threshold. Since the index of refraction of ruby is 1.76, the number of half-wavelengths along the rod for the 6943 A line is $\sim$700,000, and the optical frequency shift to increase this number by one should be 606 Mc/s.

The TWT is a Sylvania type 530. The standard barium–strontium oxide cathode and resulting electron beam are 1.77 mm in diameter, and the helix is 2.5 mm in diameter and 21.6 cm long. The tube normally amplifies from 2500 to 4000 Mc/s, with a beam current of 3 ma, a gain of 40 db, and a saturated power output in excess of 10 Mw. In many of our experiments, the filament voltage was reduced from the normal 6.3 v to 2.5 v, giving a temperature-limited beam current of 0.5 ma and a gain of $\sim$10 db along the helix. The gun end of the TWT was slid out of the focusing solenoid, with little deterioration of the electron beam focusing, until the cathode surface was visible through the glass tube envelope, looking in between the focus electrode and the first anode, at a slant angle from the cathode surface plane of $\sim$30°. The laser output was crudely focused onto the cathode from 30.5 cm away with a small lens. Experiments on this and similar cathodes showed that from 1 to 500 μa of photocurrent could be produced from the oxide cathode, with the cathode either hot or at room temperature, and with or without thermionic current being drawn simultaneously.

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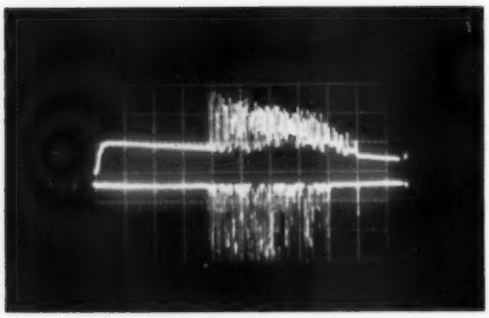

Fig. 1. Upper trace: light output from the laser. Lower trace: microwave output from the TWT helix. Sweep speed: 100 μsec/div. Sweep triggers at start of laser pumping flash.

Observations

Figure 1 is typical of the observations. The upper trace from the double-beam oscilloscope is the light output from the laser (including leakage light from the pumping flash) as monitored by a separate phototube at the opposite end of the laser rod. The lower trace is the microwave output from the TWT after amplification by two more TWT's in cascade and detection with a video crystal. Observations like Fig. 1 have also been made with superheterodyne microwave receivers. No outputs are observed except at the discrete frequencies stated above.

Figure 2 shows the same quantities, except that the sweep rate is greatly increased and the rf output at only one frequency is observed with a superheterodyne receiver following the photo-TWT. The segment shown comes from near the middle of the much longer laser oscillation pulse. An input from a microwave signal generator at the −50 dbm level to the helix input of the TWT produces about the same deflection as in the lower trace. The microwave outputs at two different beat frequencies can also be displayed separately but simultaneously on the two traces. In general, there are fewer spikes at the higher frequency, and the spikes at the two frequencies are *not* coincident in all cases. This serves as evidence that we are seeing beats between modes separated by the appropriate number of mode intervals, rather than harmonics of the fundamental 600 Mc/s frequency produced somewhere in the system.

In addition to these basic observations, we have made and are continuing the following studies:

1. By mixing the microwave output at, say, 2400 Mc/s with the c-w output of a signal generator at about the same amplitude level and a few Mc/s away in frequency, we have obtained "dc beats" within each spike which can be directly displayed on the fast oscilloscope. These beats appear to be clean and continuous, indicating that the microwave photo-beat from the TWT is essentially monochromatic. The "dc beat" frequency appears to be different from spike to spike. By studying this in more detail, and by using other means to measure the microwave frequency precisely on a spike by spike basis, we hope to distinguish photo-beats between different transverse as well as axial modes.

2. The experiments have also been repeated with a 5 cm laser rod, and the first through third mode intervals observed at 1450, 2900, and 4350 Mc/s.

3. Preliminary studies of the dependence of these beats on power input near the threshold indicate that considerable information on mode jumping within the laser can be obtained in this fashion.

All of these studies will be reported in more detail in a later publication.

Conclusions

We draw the following conclusions from these observations:

1. We are observing photo-beats as asserted above. The small discrepancy (~1%) between the calculated and observed value for the 600 Mc/s frequency can be attributed to several causes which it does not seem useful to enumerate.

2. Therefore, the ruby laser oscillates simultaneously in a number of axial modes at once, separated by up to at least 7 mode intervals. Two axial modes have been observed simultaneously in a gaseous optical maser, but to the authors' knowledge no more than this.[3] Different axial modes have also been observed in the output of ruby optical masers by high-resolution spectroscopic methods, but the simultaneous use of

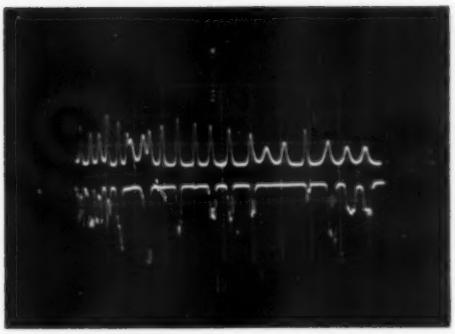

Fig. 2. Upper trace: light output from the laser. Lower trace: microwave output from the TWT helix at one particular frequency. Sweep speed: 10 μsec/div. Sweep interval is near middle of laser oscillation period.

high-speed camera techniques would be required to discover if these outputs were simultaneous.

3. The spectral width of the microwave outputs appears to be essentially the ~2 Mc/s width set by the $^1/_2$ μsec length of the spikes. Therefore, either the different axial modes are at least this monochromatic, or else the modes are coherently related to each other so as to produce coherent beats. Note that the frequency resolution involved is nearly an order of magnitude better than has previously been possible using high-resolution optical spectroscopy with a resolution of about 15 Mc/s.[4]

4. Photomixing of optical signals is possible up to at least 4500 Mc/s, which is somewhat higher than has previously been reported.[1]

5. The use of microwave phototubes has significant implications for communications employing microwave-modulated light. The experiments reported here verify a number of suggestions for constructing amplifying microwave phototubes presented by the authors at a recent conference.[5] The tube reported here is essentially an optical superheterodyne receiver with a microwave i.f. bandwidth. The cathode is the mixer, and the helix section is the i.f. amplifier. The "photo-klystron" used in the 1955 experiments of Forrester *et al.*[1] is the predecessor of this device. As suggested by Forrester in the more recent paper, we are presently preparing to carry out experiments involving the beating together of two different ruby lasers.

We are grateful to Sylvania Microwave Device Operations, Mountain View, California, for supplying the TWT's and also for supporting one of us (B. J. M.); to Tektronix, Inc., for the loan of the oscilloscope; to Prof. W. W. Anderson and Drs. F. T. Arecchi and M. Stitch for helpful comments; and to Mr. Leonard Dague and Mr. Donald McLaren for skilled assistance in constructing the laser.

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continued from p. 84

been elected President of the Optic-Electronic Corporation where he is responsible for administration of the corporation activities as well as for the design of electronic and infrared systems and development engineering. Before joining Optic-Electronic Mr. Bain was a Senior Engineer in the Electro-Optics branch of Texas Instruments where, for four years, he had directed major infrared systems engineering .... Texas Instruments recently announced the appointment of **Thomas Eugene Smith** as their Branch Manager of Electro-Optics in Dallas. Prior to his present assignment, Mr. Smith was Texas Instruments' Manager of Design and Development responsible for engineering in the Missiles and Space Department. He has presented several papers in the field of transistorized electronic circuits and has one patent pending on a three-dimensional modular circuits packaging technique .... **Tyra A. Fox** has joined the Optic-Electronic Corporation of Dallas, Tex., where he will direct design and development of optical systems. Mr. Fox had been with Texas Instruments since 1957 as an engineer designing optical systems; he contributed to the design and construction of an automatic fringe counting interferometer, a vacuum coater transmission monitor, a ruby laser, and low temperature equipment, and was the author of an optical design manual .... **Harry Wesseley,** formerly of University of Chicago Laboratories for Applied Science, has joined the Aerospace Corporation in El Segundo, Calif.. . . **R. E. Eisele,** formerly of Space Technology Laboratories, has joined Aeronutronic, a Division of Ford Motor Company, at Newport Beach, Calif.

Infrared went into the toy industry this Christmas with the *Astro-Phone,* an "infrared walkie-talkie" developed by Infrared Industries, Inc., Santa Barbara, Calif.

The U.S. Air Force is now able to save countless man hours through the use of a new high-speed system for printing identifying material on aerial photographs. This system was designed and produced by the **Eastman Kodak Co.** and **Xerox Inc.,** with Photomechanisms, Inc., for Melpar Inc.

Construction has been in progress on the unusual solar telescope planned as part of the *Kitt Peak National Observatory,* Tucson, Ariz., under the sponsorship of the National Science Foundation. This telescope involves a 115 m hole, 4.5 m in diam, bored into the top of Kitt Peak as a reflecting cage, an image being shot against a mirror in its base from a heliostat tracking the sun from 34 m above the ground. The image then reflects 85 m to a mirror that delivers it to an observation room where, as large as 85 cm in diameter, it can be photographed or studied spectroscopically. The Kitt Peak instrument will form images of the sun several times larger and more brilliantly illuminated than will any presently known solar telescope, and it is expected to be ready in 1962. It will be made available by NSF to all qualified scientists for research.

The Optical Publishing Company has issued the seventh (1961) issue of the *Optical Industry Directory* at $7.50. This is the only listing (200-page) of the one thousand companies in America who manufacture instruments and components, and who supply the services available from the optical industry. A revised lens appendix makes current the information concerning the commercially available lenses for photography and optical instrumentation (see page A24).

Bausch and Lomb, Inc., announce .... that they have appointed **William S. Fujimura** a Section Head of their Photographic Lens Section. He has specialized in the development of photographic and projection lenses and related photographic apparatus .... the completion of the **largest quartz lens** ever built, made of optical-grade quartz, 0.91 m in diameter, 0.15 m thick at the center, weight 160 kg. Despite its size, it was ground to

the same high tolerances of the B&L microscope lenses and it will be part of an optical solar simulation system, contained in a seven-story high space environmental chamber, designed and fabricated for the Jet Propulsion Laboratories, Pasadena. The lens is companion to one of optical-grade boro-silicate glass which will also go to J.P.L. Analysis shows that, when in place and under operating conditions, either lens will be subjected to a total force of about 7.25 metric tons. Planned operation date for the complete chamber was last month, some eighteen months after **Joseph F. Hall, Jr.,** Senior Physicist in B&L's Military Products Division, conceived the idea of putting the sun into a seven story building in order to provide answers about the atmosphere and solar radiation that need to be known before a spacecraft leaves its launching pad .... that they have designed a 90 mm $f/1.0$ lens for use in General Electric's new Fluoricon x-ray image intensifier. This fluoroscopic system uses mirror magnification, closed-circuit TV, and motion pictures to present x-ray images. The relay lens system picks up the image from a phosphor screen rather than directly from the x-rays, and is designed to photograph in the region of 0.550 micron light. The five-element design of the optical system produces greatly increased light transmission and uniformity of screen illumination. One of the unique parameters of this lens is the extremely high degree of aberrational correction obtained without resorting to aspheric surfaces—which fact also contributes to the economy with which the lens may be manufactured.

Current Review of the Soviet Technical Press, distributed by the U.S. Department of Commerce, reports that a powerful new experimental lamp will be installed at the height of about 60 m to illuminate the entire machine-building pavilion at the Exhibition of the USSR Achievements of the National Economy. The 300-kw lamp consists of a long glass tube filled with xenon plasma through which the current flows. The luminous intensity of the lamp equals 15 million candles and its power can be increased to 500 or even 1000 kw. Three or four such lamps placed at a great height would be sufficient for illuminating a large modern city. A special cooling system for the lamp is being developed.

continued on p. 86

Properties of the Hydrogen Maser

Daniel Kleppner, H. Mark Goldenberg, and Norman F. Ramsey

Properties of the hydrogen maser and details of the apparatus are discussed. Experimental work is described which yields a new value for the hyperfine separation of hydrogen in its ground state. The result is

$$\Delta\nu = 1{,}420{,}405{,}762 \pm 4 \text{ cps.}$$

This result is based on a value of the hyperfine separation in Cs^{133} which is taken to be

$$\Delta\nu(Cs^{133}) = 9{,}192{,}631{,}840 \text{ cps.}$$

I. Introduction

Amplification through the use of stimulated emission was first accomplished with the 3-3 line in ammonia, using a molecular beam technique to give the required state inversion.[1] Since then a great many devices utilizing numerous resonance systems and a variety of inversion techniques have been successfully operated. Until recently, however, perhaps the simplest possible resonance system—the ground state of a free atom—was not utilized. This is because the magnetic dipole transition, the only transition possible in the ground state of a free atom, has radiation matrix elements which are characterized by the Bohr magneton, μ_0, approximately one hundred times smaller than μ_e, the electric dipole moment characteristic of molecular transitions. To compensate for the small size of the moment either the beam flux must be increased by approximately $(\mu_e/\mu_0)^2$, a prohibitive factor of 10^4, or the time in which the atom interacts with the field must be increased by (μ_e/μ_0). The latter possibility has been achieved recently by the use of the "storage box" technique in which the atoms are constrained to move within the volume of the storage box by collisions with the walls.[2,3] In this sense the atoms are not strictly "free," for they experience large forces during the time of a collision. However, if the time of the collision is very short, and if the forces do not seriously upset the spacing of the energy levels of interest, the atom is indeed very close to being entirely free. This has turned out to be the case for atomic hydrogen with suitably inert wall surfaces, and it has enabled the operation of a maser oscillator utilizing the $(F = 1, m_F = 0) \rightarrow (F = 0, m_F = 0)$ hyperfine transition in hydrogen. This article summarizes some of the features of the hydrogen maser and describes experimental work which has led to a new value for the hyperfine separation in hydrogen. A more complete discussion of the maser's theoretical properties is being prepared for publication elsewhere.[4] One of the authors has presented an unpublished account of the experimental work which is described here.[5]

The authors are with Harvard University, Cambridge, Massachusetts.

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II. Analysis of the Maser Oscillator

The operation of a beam type maser has been analyzed by Shimoda *et al.*[6] and with a few modifications their results can be applied to the hydrogen maser. An important difference between a conventional beam maser and the hydrogen maser is that in the former the time spent in the rf field is characterized by the fixed path length each molecule travels across the cavity and a velocity which may either be considered fixed (as in ref. 6) or is given by a modified Maxwellian distribution, while in the latter the time is described by an exponential distribution function with a decay time equal to the mean time necessary for an atom to effuse from the box. Another important difference is due to the effect of wall collisions on the resonance states in the hydrogen maser, but this will be neglected initially.

The familiar energy level diagram for the ground state of hydrogen is shown in Fig. 1. The transition of interest, $(F = 1, m_F = 0) \rightarrow (F = 0, m_F = 0)$, occurs at a frequency $\Delta\nu = 1420$ Mc/s approximately. A schematic diagram of the apparatus is shown in Fig. 2. Atoms from the source pass through the state selector which deflects toward the axis those in the $(F = 1, m_F = 1)$ and $(F = 1, m_F = 0)$ states. The beam is

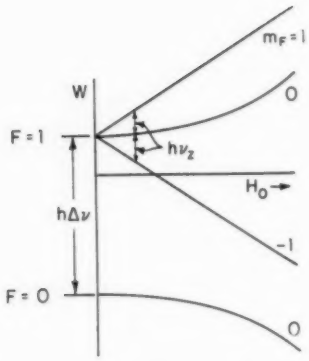

Fig. 1. Energy levels of hydrogen in its ground state.

focused on the aperture of the storage bulb, which is located in a microwave cavity tuned to the transition frequency. If the density and lifetime of atoms in the ($F = 1$, $m_F = 0$) state are great enough, oscillation due to stimulated emission occurs and a signal at the resonance frequency is detected by means of a small coupling loop in the cavity.

A. Threshold for Oscillation

The minimum flux necessary for oscillation, I_{th}, is given[4] by

$$I_{th} = \frac{h}{8\pi^2}\frac{V}{Q}\frac{1}{\eta(\mu_0 T_r)^2} \tag{1}$$

where Q is the loaded quality factor of the cavity, T_r is the mean radiation lifetime of an atom in the cavity, V is the volume of the cavity, μ_0 is the Bohr magneton, and η is a geometrical factor depending on the distribution of rf magnetic field in the cavity. Typically, $\eta \approx 3$.

For an order of magnitude estimate of the threshold flux we may take the following values: $V = 10^4$ cm^3, $Q = 3 \times 10^4$, $T = 10^{-1}$ sec. The result is $I_{th} \approx 10^{12}$ pps.

B. Noise in the Maser

The ultimate stability of the maser oscillator is governed by the influence of thermodynamic noise on the oscillation. If the maser is observed for a time t, the relative fluctuation in frequency which is observed due to noise is given[4] by

$$\frac{\langle \delta\nu^2 \rangle^{1/2}}{\nu} = \frac{1}{2\pi\sqrt{2}}\frac{1}{Q_l}\sqrt{\frac{kT}{Pt}}. \tag{2}$$

Here P is the power delivered to the cavity by the beam ($P = {}^1/_2 h\nu$ approximately in a typical case). The quality factor for the resonance is defined by $Q_l = \nu/\delta\nu_r$, where $\delta\nu_r$, the resonance width of the transition, is given by $\delta\nu_r = (\pi T_r)^{-1}$. This expression takes into account the effect of atomic amplification of the noise. With $T_r = 0.3$ sec, $I = 3 \times 10^{12}$ pps, and an observation time of 1 sec, we have $\langle \delta\nu^2 \rangle^{1/2}/\nu = 4 \times 10^{-15}$. The spectral purity of the maser is consequently very high. However, its long term stability in practice depends upon how well external influences can be controlled, some of which will be discussed below.

C. Limitations to Radiative Lifetime

The fundamental limit to the radiative lifetime of atoms in a given bulb is due to the rate at which atoms escape from the bulb. The characteristic time for this, T_b, is the mean time an atom spends in the storage bulb before effusing from the bulb aperture. This time may readily be determined from the geometry of the bulb. If the total volume of the bulb is V_b, and if the total escape area is A_e, then it can be shown that $T_b = 4V/(A_e\bar{v})$, where $\bar{v}$ is the mean velocity. As an example, a bulb 15 cm diam with a 2 mm diam aperture yields a lifetime $T_b = 0.8$ sec. There are, however, a variety of other effects which may relax the radiative state of an atom before it escapes from the bulb. Among the more important of the processes are:

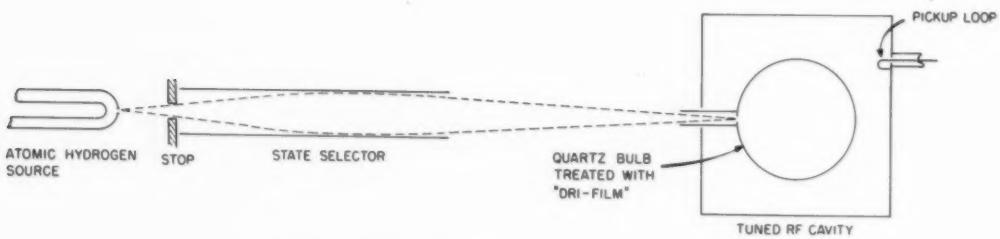

Fig. 2. Schematic diagram of hydrogen maser.

Collisions with the Walls

So far the effect of surface collisions has been neglected. The collisions can both cause a shift in the resonance frequency and broaden the resonance line. The two effects are related and can be described in terms of the parameter φ, the phase shift introduced into the wave function by a single wall collision.[3] It is shown in ref. 3 that the atom will lose its coherence with the radiation field after a number of collisions $n \approx 2/\varphi^2$. If the mean time between collisions is t_0, then the time for relaxation due to wall collisions is $T_w = 2t_0/\varphi^2$. As will be described below, φ may be determined from measurements of frequency shifts in the maser. This has so far only yielded an upper limit to φ given by $\varphi < 8 \times 10^{-4}$ rad/collision, corresponding to $T_b = 100$ sec. This is extremely large, and due to the reciprocal fashion in which relaxation times add up, may be neglected.

Spin Exchange Collisions

If all the hydrogen atoms in the cavity were in a pure state their radiation properties would be unaffected by collisions with each other. However, because of the presence of atoms in the ($F = 1$, $m_F = 1$) state, and because atoms in the radiation state have different life histories in the cavity, a collision between two hydrogen atoms will in general cause a change in the wave function of each. The most important collision process is that of spin exchange. This process has been considered in some detail by Wittke and Dicke.[7] Wittke and Dicke estimate that the relaxation time for spin exchange is related to the density of hydrogen atoms, N, by

$$T_{se} = 10^9/N \text{ sec.}$$

For a flux of 10^{12} pps, and a bulb volume of 10^3 cm^3, this corresponds to a lifetime of 1 sec. Spin exchange does not place a fundamental limit on the stability of the maser, however, since if oscillation is once achieved and if no other relaxation mechanisms are important, decreasing the flux increases the radiative lifetime in inverse proportion. There is a proportional decrease in power but, as indicated in Eq. (2), $\langle \delta\nu^2 \rangle^{1/2}/\nu$ depends linearly on the lifetime but only on the square root of the emitted power, so the net effect of decreasing the flux is to increase the stability.

Motion through Inhomogeneous Magnetic Fields

If there is an inhomogeneous magnetic field in the region of the bulb, an atom, by virtue of its motion, experiences a field which varies randomly in time. Components of the varying field occurring at $\Delta\nu$ are negligible. However, there may be appreciable intensity at the Zeeman frequency, indicated by ν_z in Fig. 1. Decay of the ($F = 1$, $m_F = 0$) state by either of the Zeeman transitions limits the radiation lifetime of the atom. In the absence of all other relaxation processes this mechanism can be characterized by the relaxation time T_H. There are two extreme conditions, corresponding to the Zeeman frequency being either large or small compared to the collision frequency of the atom with the walls. It is usually desirable to run the maser in a low magnetic field in which case the latter condition holds. The relaxation time is then related to the rms field inhomogeneity, $\langle H_i^2 \rangle$, by[4]

$$T_H = 3/(4\gamma^2 \langle H_i^2 \rangle \tau).$$

Here γ is the gyromagnetic ratio for the ($F = 1$) state, 1.4 Mc/s per gauss, and τ is a correlation time which may be taken as t_0, approximately 3×10^{-4} sec. If $\langle H_i^2 \rangle^{1/2}$ is 0.1 milligauss the radiation lifetime is 3 sec. Although lifetimes this long have not been observed so far, it appears possible to achieve fields of this homogeneity in the laboratory by the use of suitable shields. It is evident, nevertheless, that the requirements for uniformity of the magnetic field are severe.

III. Frequency Perturbations

A. Wall Collisions

During the time of collision with the wall the energy levels of the hydrogen atom may be seriously perturbed and this will be reflected in a shift in the resonance frequency of the transition, since the resonance frequency depends on the average energy separation. The frequency shift, $\delta\nu$, is related to the phase shift per collision, φ, by[3]

$$\delta\nu = \varphi/(2\pi t_0).$$

It is apparent that the shift depends on the collision rate within the bulb and will reveal itself as a systematic shift in frequency with size of the storage bulb. A search with bulbs treated with dimethyldichlorosilane, the wall coating used in the experimental work described here, has failed to reveal any such shift, which implies an upper limit for the shift in a 16.5 cm diam bulb, $|\delta\nu| < 4$ cps $\approx 3 \times 10^{-9}\Delta\nu$. A lower limit may be obtained from the measured frequency shift of the hyperfine resonance in hydrogen caused by collisions of hydrogen atoms with molecular hydrogen in a buffer gas.[8] If the pressure shift in ref. 8 is extrapolated to the collision rate characteristic of the maser the frequency shift is found to be $\delta\nu > 2 \times 10^{-14}\Delta\nu$ and this may be taken as a lower limit. The reproducibility and stability of a given surface are of fundamental importance to the operation of a maser, but as yet there is no information on these points.

B. Doppler Shift

The effects of the first order Doppler shift are suppressed in the hydrogen maser because the effective average velocity of the hydrogen is very low due to its confinement in the storage bulb. The second order

Doppler shift is unavoidable, and because of the small mass of the hydrogen atom, it is fairly sizable. The frequency shift is given by

$$\delta\nu_D = +\frac{1}{2}\frac{V^2}{c^2}\Delta\nu$$

$$= +\frac{3kT}{2mc^2}\Delta\nu$$

$$= (1.4 \times 10^{-12}T)\Delta\nu$$

where T is the temperature in °C. If the second order Doppler shift is the limiting perturbation it may be reduced by a factor of 3 by using tritium instead of hydrogen.

C. Cavity Pulling

If the cavity is mistuned from the resonance by an amount $\delta\nu_c$ then the oscillator frequency will be displaced by an amount $\delta\nu = \delta\nu_c(Q_c/Q_c)$. Since the shift decreases with increasing Q_l it does not become relatively any more significant as the lifetime increases. This expression is not exact for the case of a conventional beam maser, but must be multiplied by a slowly varying function of the power level. In the case of an exponential distribution for radiation lifetime, however, the pulling effect is independent of the power level.

D. Other Effects

Because of the lack of structure of the resonance line and the symmetry of the ($F = 1$, $m_F = 1$) and ($F = 1$, $m_F = -1$) states, a number of perturbations which affect a molecular maser are either absent or very small in the case of the hydrogen maser.

IV. Apparatus

A. Wall Coating

The storage bulbs which were used in the present experiments were treated with dimethyldichlorosilane (General Electric "Dri-Film," SC-02). This compound was used by Wittke and Dicke[7] to prevent surface recombination of atomic hydrogen, and has been used to prevent hyperfine relaxation of alkalis in optical pumping experiments.[8] The surface is treated either by placing a few drops of the liquid in a carefully cleaned bulb and letting the vapor interact with the walls, or by flowing the vapor through the bulb in an inert carrier gas.

B. Source

The machine used for the present experiments has a Wood's discharge source. However, an rf discharge appears to work equally satisfactorily, and has the advantages of smaller volume and much less power dissipation. Some of the relevant characteristics of rf source are: hydrogen prsesure, 0.3 mm Hg; discharge tube size, 9 mm i.d. and 11 mm o.d.; exit orifice, 0.8 mm diam; frequency, 14 Mc/s; coupling, electric; electrodes, external, 8 cm separation; power, about 30 watts.

C. State Selector

State selection is accomplished by means of a hexapolar magnetic field. Both electromagnets and permanent magnets have been used. The latter seems more satisfactory and is much simpler in construction. A magnet similar to the design of Christenson and Hamilton,[10] but with slightly larger poles, yields a maximum field at the pole tips of 9900 gauss. The gap is 3 mm diam and 7.5 cm long. The calculated solid angle for the desired state, assuming a 2 mm image diameter, is 3×10^{-5} ster.

D. Electronics

The present measurements were made completely in terms of a National Company Atomichron which is located in the laboratory of J. A. Pierce. The frequency measuring system is indicated in Fig. 3. Auxiliary apparatus for tuning the cavity, and for measuring the radiation lifetime by a transient technique, are not shown.

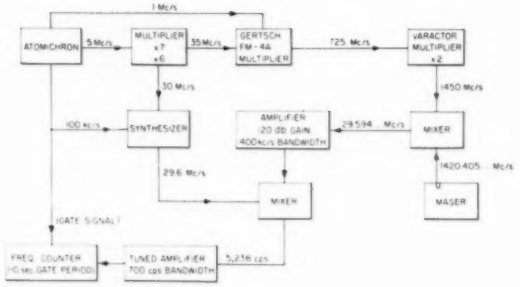

Fig. 3. Frequency measuring system.

E. Magnetic Field

The measurements described here were all carried out with the maser cavity surrounded by three orthogonal pairs of correction coils which served to cancel most of the earth's magnetic field. However, the combination of inhomogeneities imposed by the coils and residual inhomogeneities in the laboratory prevented oscillation at fields below 60 mgauss, and most measurements were taken at 80 mgauss. Fluctuations in the magnetic field due to activity of a nearby subway during the day were large enough to require measurements to be taken late at night.

The magnetic field was measured by a double resonance technique in which a signal at the Zeeman frequency is applied to the maser by means of an external coil while the oscillation level is measured. The effect of the low frequency signal is to mix the Zeeman states, thereby reducing the radiative lifetime of atoms in the ($F = 1$, $m_f = 0$) state, with a consequent diminution in radiated power. The line width of the Zeeman resonance was typically 2 kc/s.

F. Cavity

A cylindrical cavity operating in the TE_{011} mode was used. The unloaded Q of the cavity is approximately 53,000. Tuning is accomplished by a sliding end plate, and a fine tuning plunger. The resonant frequency could be measured to 250 cps by monitoring the absorption curve, using a phase-locked oscillator as the signal source.

V. Experimental Procedure

The routine followed in measurements of the hyperfine frequency of hydrogen was as follows: the cavity resonance frequency and loaded Q were first measured. This was followed by a Zeeman frequency measurement as described in Section IV, E. A series of ten measurements of the 5.7 kc/s beat frequency between the maser and the Atomichron were then made with a frequency counter, each measurement taking 10 sec and having an uncertainty due to the counter of ±0.1 cps. Zeeman measurements alternated with hyperfine measurements for six such sequences. The run was completed by remeasurement of the cavity resonance frequency.

The large number of measurements was necessary in order to average out a short term fluctuation in the Atomichron which was adjusted for long term stability and consequently has an underdamped servo loop. Measurements taken with a second Atomichron which was properly adjusted for short term stability consistently gave readings differing only by the inherent counting error. However, since the first Atomichron was monitored against other standards all the data were taken with it as the standard.

The radiative lifetime in all the measurements was approximately 0.3 sec.

VI. Results

A total of 25 runs was made with two bulbs, one 16.5 cm diam and the other 11.4 cm diam. The results are shown in Fig. 4. The following corrections were made to the data:

Magnetic field. The field present, about 80 mgauss, shifts the resonance frequency about 18 cps. The Zeeman frequency could be determined to an accuracy of 100 cps, and the consequent uncertainty introduced by this into the final result is 0.03 cps.

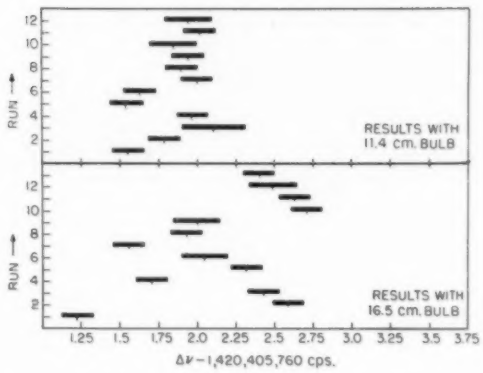

Fig. 4. Experimental results with two different size bulbs (uncorrected for second order Doppler shift).

Cavity pulling. The cavity was always tuned to within 1.5 kc/s of the hyperfine frequency, and the correction for pulling was at most 0.05 cps. The uncertainty of 300 cps in the cavity resonance frequency corresponds to an uncertainty of 0.01 cps in the cavity pulling correction.

In addition, a correction of −0.06 cps, due to the second order Doppler shift, was made to the final results (not indicated in Fig. 4). With this correction, the results for the two bulbs are:

16.5 cm diam bulb $\Delta\nu = 1{,}420{,}405{,}761.78 \pm 0.7$ cps.

11.4 cm diam bulb $\Delta\nu = 1{,}420{,}405{,}762.11 \pm 0.4$ cps.

These frequencies are in terms of the cesium hyperfine frequency which is taken as $\Delta\nu_{Cs} = 9{,}192{,}631{,}840$ cps. There is no apparent systematic shift in frequency between the bulbs. However, the deviations among individual runs are much larger than can be explained by the uncertainties mentioned above. The cause for these deviations was not determined. However, if the difference between the two results is assumed to be due entirely to a wall shift then the phase shift per collision is found to be $\varphi = +1.9 \times 10^{-4}$ rad/collision. This corresponds to a frequency shift $\delta\nu = 0.8$ cps for the larger bulb. If the extreme frequency difference between the two bulbs is used to determine maximum possible limits to the wall shift the result is $|\varphi| < 8 \times 10^{-4}$ rad/collision, or $|\delta\nu| < 4$ cps. This latter figure will be taken to be the maximum uncertainty in the final result, which is

$$\Delta\nu = 1{,}420{,}405{,}762 \pm 4 \text{ cps.}$$

Although this is slightly higher than the published value of Anderson and Pipkin,[9]

$$\Delta\nu = 1{,}420{,}405{,}726 \pm 30 \text{ cps},$$

it is in close agreement with the more recent unpublished value of Lambert and Pipkin[11]

$$\Delta\nu = 1{,}420{,}405{,}748 \pm 7 \text{ cps},$$

and falls within the limits of measurements by Wittke and Dicke[7] and Kusch.[12]

The authors wish to acknowledge the help of Norval Fortson and Howard Berg in the construction of some of the apparatus and for assistance in taking data, and wish to thank J. A. Pierce for providing the frequency standard. One of the authors (H. M. G.) wishes to acknowledge the support of an NSF Predoctoral Fellowship during the period of this work.

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Principles of Operation of the Rubidium Vapor Magnetometer

Arnold L. Bloom

This paper discusses some of the basic problems involved in designing and using a magnetometer employing optical pumping. Particular attention is given to magnetometers of the self-oscillating type; i.e., those that are analogous to masers in that the resonant properties of the spin system itself are used to sustain continuous oscillation at the resonant frequency. Among the topics treated are amplitude variations with orientation, sensitivity, behavior in extremely weak magnetic fields, and response to rapid field changes.

One of the most important of the practical applications of optical pumping has been to the precise measurement of weak magnetic fields. To this end, several magnetometer systems have been developed using either alkali metal vapor or triplet metastable helium as the rf resonant element. A number of these devices are currently in use for measurement of the geomagnetic field at or near the surface of the earth, and several rubidium vapor magnetometers have been flown in space vehicles. One of these latter instruments successfully measured the interplanetary field out to a distance of 10 earth's radii. This paper discusses the theoretical basis of these Rb space magnetometers, although emphasis is also placed on those problems that arise in operation at the surface magnetic field of about 0.5 gauss. Much of the theory developed here applies to metastable helium magnetometers as well.*

I. Fundamentals

The basic theory around which all these instruments are designed was presented in earlier papers by Dehmelt,[1] and by the author and W. E. Bell.[2] All of these systems share the following apparatus in common: A light source producing an intense collimated beam of resonance radiation,[3] a circular polarizer, an absorption cell containing the vapor to be optically pumped, a radio-frequency coil to produce resonance in the pumped vapor, and a photocell to monitor the transmission of the light. Also under certain circumstances it may be necessary to use a filter capable of eliminating some of the fine structure components of the resonance radiation prior to its entering the absorption cell. A detailed discussion of the conditions under which such a filter must be used will not be undertaken here, except to point out that it depends on the pressure of the buffer gas, if any, that is used to reduce the rate of collisions of the atomic vapor with the walls. The rubidium magnetometers described here normally employ a fairly high pressure buffer gas (3 cm Hg or higher) of neon and a filter is needed to pass the resonance radiation at λ 7948 and reject λ 7800. An interference filter has been developed for this purpose* which transmits approximately 80% of the λ 7948 radiation for rays whose deviation from the perpendicular is as great as 15°.

The change in optical transmission of the spin system upon application of a resonance rf field has been discussed earlier[1,2] and depends in detail on the direction of the incident light beam relative to the constant magnetic field. The behavior of the spin system can be described by the three variables M_x, M_y, and M_z of Bloch's equations for a spin system,[4] and the signal present at the photocell is proportional to M_n, where n is the direction of the light beam relative to the magnetic field. More specifically, the types of signals that may be observed may correspond either to M_z, giving rise to a secular change in light intensity, or to M_x or M_y, which manifests itself as a high frequency light modula-

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* For a more detailed comparison of these two types, see P. L. Bender, *Compt.-rend de 9e Colloq. Ampère*, Librairie Payot, Geneva, 1960.

* Manufactured by Spectrolab, Inc., Los Angeles, California.

tion synchronized with the driving rf field. These two types of signals can be readily separated in the electronics following the photocell by virtue of their differences in frequency, and make possible a variety of systems in which the photocell signals can be employed to give information as to the value of the resonant frequency and hence the magnetic field.

It is well known that all magnetometers employing a Larmor resonance have a resonant frequency directly proportional to the applied magnetic field, independent of the angle made by the apparatus relative to the direction of the field. However, the signal amplitude may be a function of this relative orientation. In all of the presently developed optically pumped magnetometers, circularly polarized radiation is employed both as the pumping agent and as the detecting agent. From the symmetry properties under rotation inherent in circular polarization the following angular dependence applies: (1) The secular pumping process varies as $\cos\theta$; (2) detection of the secular light modulation M_z varies as $\cos\theta$; (3) generation of free spin precession varies as $\sin\theta$; and (4) detection of the Larmor frequency modulation M_x or M_y varies as $\sin\theta$, where θ is the angle between the polar vector defined by the polarized light and the magnetic field H_0. The types of angular dependence that may be observed in the magnetometer, as a system, may therefore depend on $\sin^2\theta$, $\cos^2\theta$, or $\sin\theta$, $\cos\theta$, depending on what combinations of pumping and detecting mechanisms are used. Now, for space exploration purposes, one has to assume that the light beam vector may have an equal probability of being in any position relative to the magnetic field. If the signal S is defined as $S = 1$ when the instrument is in its most favorable orientation, then we can calculate the probability $(dP/dS)\Delta S$ that the signal will have an amplitude between S and $S + \Delta S$. It is calculated from the following:

$$dP(\theta)/d\theta = \sin\theta,$$

then

$$\frac{dP}{dS} = \frac{dP(\theta)/d\theta}{dS(\theta)/d\theta}$$

and the right-hand side is solved in terms of S. The result is

$$\frac{dP}{dS} = \frac{1}{2\sqrt{S}}$$

for $S = \cos^2\theta$ or $S = \sin\theta\cos\theta$;

$$\frac{dP}{dS} = \frac{1}{2\sqrt{(1-S)}}$$

for $S = \sin^2\theta$.

These results are plotted in Fig. 1. All of the devices discussed here follow curve A and due allowance must therefore be made for the high probability of the instrument having a relatively unfavorable orientation and weak signal. Until recently, no practical instruments had been suggested that might have a response given by curve B. However, the recent observation of optically driven spin precession,[5] which has a $\sin^2\theta$ dependence, makes such a magnetometer feasible[6] and suggests a close examination of the behavior and requirements of such magnetometers. This is not attempted in this paper.

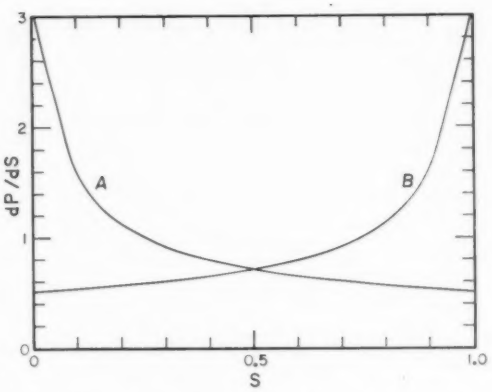

Fig. 1. Differential probability of obtaining a signal of amplitude S. Curve A: $S = \cos^2\theta$ and $S = \sin\theta\cos\theta$. Curve B: $S = \sin^2\theta$.

II. Possible Systems

Three types of systems have been developed into practical magnetometers.

The first of these[7] is shown in Fig. 2, and employs the

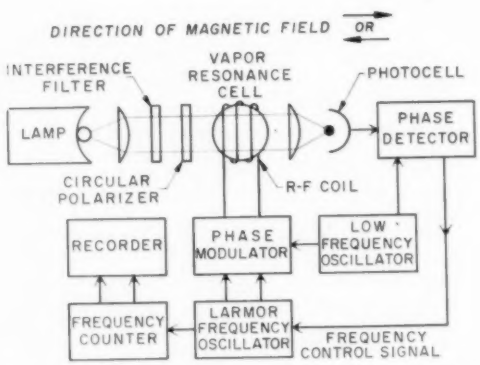

Fig. 2. Block diagram of magnetometer employing M_z signal and phase detector to stabilize a local oscillator at the Larmor frequency. Minor variations of this scheme may employ magnetic field sweep, low-frequency offset oscillators, or servo loops responsive only within a certain range of frequencies.

M_z signal. A small frequency modulation is applied to the local rf oscillator to sweep the rf back and forth through resonance. The photocell signal then has strong components at even harmonics of the modulation frequency if the sweep is centered about the resonance. Any deviation gives rise to a fundamental component which is phase detected and used to servo the tracking rf oscillator. The angular dependence of the signal varies as $\cos^2\theta$. This type of system does not place severe restrictions on the performance of the photocell or its amplifier, and it employs a type of electronic detection system that is well known in the art of magnetic resonance. It has been widely employed to demonstrate the operation, in principle, of optically pumped magnetometers. However, for airborne and space applications, where power and weight requirements are at a premium, this type of system does not possess the advantages of extreme simplicity and wide dynamic range that are characterized by the next two systems to be described. Accordingly all of our present work in Rb vapor magnetometers is concentrated on these two latter types of systems. The remainder of this paper will be concerned primarily with them.

The next system to be described will be designated as the "single cell self-oscillator" and is shown in Fig. 3.

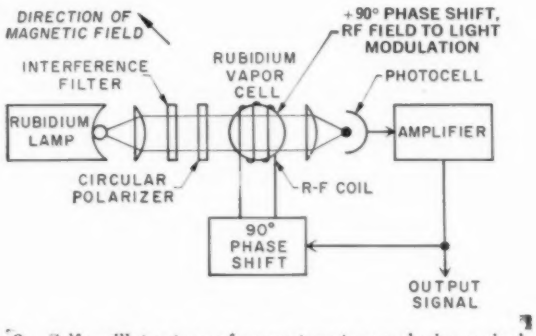

Fig. 3. Self-oscillator type of magnetometer employing a single absorption cell.

Here the photocell observes the signal corresponding to M_x, which is at the driving radio frequency, and whose phase relative to the driving rf field varies near resonance in much the same way as the phase of the circulating current in a tuned resonant circuit. The photocell signal is fed back through suitable amplifiers and phase shifters to the rf coil and maintains a closed loop through which information can be transmitted only within the resonance line width. This system will oscillate spontaneously at the resonant frequency if the

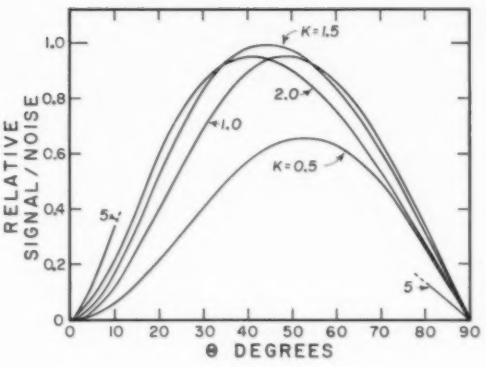

Fig. 4. Signal amplitude or signal-to-noise ratio of the self-oscillator as a function of θ. These curves differ from the simple $\sin\theta\cos\theta$ dependence in that they include the effect of variation of the perpendicular component of the rf field. $K = \gamma H_a(T_1T_2)^{1/2}$ where $2H_a$ is the peak value of the alternating rf field along the coil axis.

gain of the loop is unity and the sum of all phase shifts in the loop is zero. In order to reduce the number of axes of symmetry to a minimum, the rf coil is wound coaxial with the light beam so that only the one angle θ suffices to describe all variations in performance such as are shown in Fig. 4. (If the rf coil axis were perpendicular to the light beam, then the phase shift would vary with rotation of the instrument about the light beam axis.) The component of rf field H_1 perpendicular to H_0 defines the x-direction, and correspondingly the alternating signal observed by the photocell always corresponds to M_x, rather than to M_y or some linear combination. Bloch's equations predict a 90° phase shift between H_1 and M_x at exact resonance, and this is the reason for the 90° phase shifter.

The system just described has the following disadvantage: In the angular dependence of the signal as given by $\sin\theta\cos\theta$ or in Fig. 4, the change in sign which occurs at $\theta = 90°$ must be taken literally. It corresponds to the fact that if the instrument is properly phased for $0 < \theta < 90°$, then it is wrongly phased for $90° < \theta < 180°$. An engineering solution to this problem has been obtained by including, in the feedback loop, a "signal searcher" which periodically interchanges the connections of the rf coil until oscillation is established. However, a much more elegant solution is that of the third system to be described, shown in Fig. 5, which will be designated as the "two-cell self-oscillator system." This system consists of two identical optical systems in which one photocell output is used to drive the rf coil of the complementary absorption cell. It may be described most simply by saying that each optical system acts as a 90° phase shifter for the other. Here the sum of the phase shifts of the entire feedback loop can be made zero without

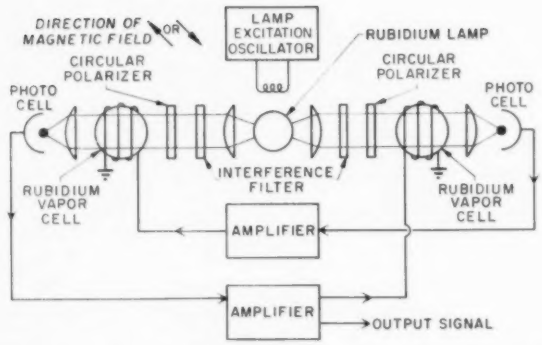

Fig. 5. Self-oscillator employing two absorption cells. If the two optical systems are placed back-to-back, as shown, then the two circular polarizers should be of the same sense (e.g., right-handed) to preserve symmetry upon 180° rotation.

insertion of electronic phase shifters and the device has complete symmetry for 180° rotations, so that it will oscillate spontaneously in all directions except $\theta = 0$ or 90°.

Both of the above types of instruments have been flown in space vehicles.

III. Theoretical Sensitivity

For our purposes we are concerned with two aspects of sensitivity: (a) the smallest absolute value of the field that can be measured by the apparatus (important for interplanetary field measurements) and (b) the smallest increment in magnetic field, at some reasonable ambient level, which can be measured.

The smallest absolute value of field that can be measured by any Larmor resonance apparatus is roughly equal to the rf resonance line width expressed in magnetic field units, since at smaller values the response is no longer that of a resonant system. This point is elaborated on in Section IV, where the problems involved in reaching the limit are defined more precisely. The total line width Γ of the resonance is given in general by

$$\Gamma = \Gamma_r + \Gamma_t$$

where Γ_r represents the effect of absorption of resonance radiation and Γ_t, due to thermal relaxation, is the minimum line width that is obtainable in the limit of zero light intensity (and therefore in the limit of zero signal-to-noise ratio!). For the alkali vapors, Γ_t has been found[1] to be of the order of 0.03 cps. For Rb^{87}, which has as high a g-factor as can be found in any of the alkali isotopes, the gyromagnetic ratio is 700 kc/s per gauss so that the above number corresponds to a minimum magnetic field of less than 10^{-7} gauss. As a practical matter, however, including line broadening from the light, the minimum measurable field appears to be about 2.0×10^{-5} gauss. Metastable helium, whose gyromagnetic ratio is 2.8 Mc/s per gauss, appears to have a minimum line width of about 10^3 cps corresponding to 40×10^{-5} gauss.

The sensitivity of the instrument for small increments of field depends in part upon line width, and in part upon actual signal-to-noise ratio for the resonance signal itself. Because of the success of theoretical signal-to-noise calculations in nuclear and electron spin resonance, it is attractive to attempt the same sort of calculation for an optically pumped system. Unfortunately, the problem in this case is made difficult by the large number of variables whose effect on performance is difficult to assess experimentally, much less theoretically, and because comparison with a standard is not available. For a given configuration we might proceed as follows. If we start with the assumption that the light source is perfectly incoherent, and that the photocell has unity quantum efficiency and zero dark current, then the noise current N is given by

$$N = (2e^2nB)^{1/2}$$

where e is the electronic charge, n is the number of photons per second, and B is the effective bandwidth; in this case $B = \Gamma$. Since Γ_r is proportional to n, we have

$$N \propto (\Gamma\Gamma_r)^{1/2}.$$

The relative signal current, S, is calculated in formula (10a) of I and can be written as

$$S \propto \Gamma_r^2/\Gamma.$$

The sensitivity of the instrument for small changes in field in its optimum orientation is then given by

$$\frac{S}{N\Gamma} = \frac{\Gamma_r^{3/2}}{(\Gamma_r + \Gamma_t)^{3/2}}.$$

This has a maximum at $\Gamma_r = {}^3/_2\Gamma_t$, suggesting operation with narrow lines and weak light. In practice, however, other sources of noise are also present and it is usually found desirable to operate with the highest possible light intensity consistent with other requirements. Typical operating conditions, for moderately strong magnetic fields and illumination, are approximately as follows: Average photocurrent, about 1.0×10^{-4} amp; noise, $N = 1.65 \times 10^{-9}$ amp; signal, about 1% of average photocurrent or about 1.0×10^{-6} amp; line width at this light intensity, about 100 cps. The minimum detectable change in frequency, $N\Gamma/S$, is then about 0.025 cps corresponding to a field change of 3×10^{-8} gauss for Rb^{87}. This is comparable to experimentally determined results and suggests that photoelectron shot noise is indeed the limiting factor for this particular configuration. At lower light intensities, dark-current or amplifier noise seems to predominate. This might be avoided by increasing the

diameter of the optical system from the present 5 cm, while maintaining good optical geometry so that the size and brightness of the image on the photocell is comparable to that now available. An increase in diameter, however, is incompatible with size and weight limitations for space applications.

IV. Perturbations from the Larmor Resonance Condition

Up to now, we have specified that the oscillation frequency of either of the two self-oscillating magnetometers is actually the Larmor (angular) frequency $\omega_0 = \gamma H_0$. However, we must be concerned about the possibility of deviations from this condition, for two reasons. First, we demand that the magnetometer measure field increments much smaller than the resonance line width. Since the usual first-order perturbation theory leading to a description of resonance effects is good only to within orders of magnitude of the line width, it is therefore apparent that we must look for higher order effects. Second, operation of the magnetometer in extremely weak fields may bring us close to the condition where the spin system is no longer recognizable as a resonance system, and in that case we must be concerned as to exactly how far we can push the operation of the system toward zero magnetic field. We shall consider the effect of variations of phase in the feedback loop, and then go on to effects intrinsic to the spin system that have not been discussed so far.

Phase Relationships

In the vicinity of resonance, the amplitude of the received signal M_x is approximately constant (it is maximum by definition), but the phase varies as $\mathrm{ctn}^{-1}\ (T_2\Delta\omega)$, where $1/\pi T_2$ is the line width (in ordinary frequency units) and $\Delta\omega$ is the deviation from resonance.* It is clear from this that even with the narrowest lines that are conveniently available, say 15 to 100 cps, the phase of the feedback loop and of the received signal M_x must be held constant within 0.1° or better if the magnetometer is to retain its potential sensitivity. Most of the problems that are experienced in practice, in maintaining correct phase relationships, are electronic ones that will not be of concern here. We will mention one additional problem—that of effects of misorientation of the mean axis of the rf coil. If the coil axis is not exactly parallel to that of the light beam, then the coaxial symmetry which was discussed earlier is partially destroyed and orientation effects can show up in the form of spurious phase shifts. The maximum possible shifts are shown in Fig. 6. The figure shows that serious effects occur only when θ is small; however, under such conditions even a small misorientation angle can give rise to a large error. Special care is therefore required in winding the rf coil about the absorption cell and maintaining it rigid with respect to the external supports, also in maintaining an optical system with well-defined axis of symmetry despite the broadness of the source.

Higher Order Terms in Bloch's Equations

In I there was developed a solution to the equations of motion of a spin-$^1/_2$ optically pumped system based on Bloch's equations. It was pointed out there that, although the equations held strictly only for spin-$^1/_2$ particles, it was hoped that they might find more general application for the more complicated spin system which actually represents a Rb atom. Experience under a wide variety of conditions has shown that these equations do indeed give a quite accurate representation of the behavior of the signals, except for some specific instances where the hyperfine coupling results in a multiplet structure. These situations are dealt with later. We are concerned here with those deviations from the normal resonance conditions that can be predicted within the scope of Bloch's equations. These effects are particularly important in very weak fields.

In I we developed a Fourier expansion of Bloch's equations in terms of components at the driving frequency and its harmonics. The expansion is as given overleaf

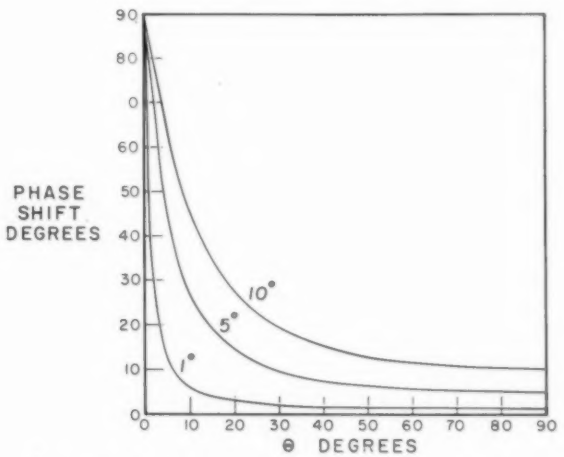

Fig. 6. Phase shift in the photocell signal as a function of orientation angle, θ, shown for three misorientation angles of the rf coil axis relative to the optical axis.

* From this point on, the mathematical notation is identical to that employed in I except that S_1, S_2 are replaced by the more conventional symbols T_1 and T_2. T_1, T_2 are relaxation times including lifetime-shortening effects of the light.

$$M_x + iM_y = \sum_{n=-\infty}^{\infty} f_n e^{in\omega t},$$

$$M_z = \sum_{n=-\infty}^{\infty} m_n e^{in\omega t}.$$

Of the various coefficients, f_1, f_{-1} and $m_1 (= m_{-1}^*)$ are at the driving frequency itself and can therefore all take part in the signal contained in the feedback loop. The other terms can be considered as perturbations contributing to the final solution, and of these only the terms with $|n| \leq 2$ will be different from zero except under the most extreme conditions. Solution of Eqs. (14a) and (14b) of I for a weak H_1 field ($m_0 \approx M_0$) gives the following for M_{osc}, the magnetic moment oscillating at the driving frequency. With the phase chosen by $H_x = 2H_1 \cos \omega t$ we have:

$$M_{osc} = M_x \sin\theta + (M_z)_1 \cos\theta,$$

$$M_x = \gamma H_1 M_0 \left[\frac{\omega_0 + \omega}{T_2^{-2} + (\omega_0 + \omega)^2} + \frac{\omega_0 - \omega}{T_2^{-2} + (\omega_0 - \omega)^2}\right]\cos\omega t$$

$$- \frac{\gamma H_1 M_0}{T_2}\left[\frac{1}{T_2^{-2} + (\omega_0 + \omega)^2} - \frac{1}{T_2^{-2} + (\omega_0 - \omega)^2}\right]\sin\omega t,$$

$$(M_z)_1 = \frac{2\gamma H_1 T_1 T_2 \omega_0 M_0' (\cos\omega t - \omega T_2 \sin\omega t)}{(1 + T_1^2\omega^2)(1 + T_2^2\omega_0^2)}.$$

The M_x part of the equation consists of the usual resonance expression plus additional terms that take into account the fact that the alternating rf field really contains two frequencies, $+\omega$ and $-\omega$, and each of these must act independently upon the spin system. The extra terms cannot be ignored in weak fields. They give rise to a deviation in the apparent Larmor frequency, in that the frequency for which there is a 90° phase shift is given by

$$\omega = [(1/T_2)^2 + \omega_0^2]^{1/2}.$$

The effect may be of importance even when the field differs from zero by several line widths. It represents, however, a fixed correction that can be included if T_2 is known.

Simultaneous with the shift in phase relationships is a change in signal amplitude. The signal amplitude at the frequency at which there is 90° phase shift is proportional to $\omega_0 [(1/T_2)^2 + \omega_0^2]^{-1/2}$ if H_1 is held fixed and more nearly proportional to ω_0^2 if $H_1 < H_0$. It is apparent from this that one can get self-oscillation in fields much smaller than a line width if signal-to-noise is available; however, it is also clear that there will not be much sensitivity for variations of the "true" Larmor frequency in this case.

The effect of the $(M_z)_1$ term is to introduce additional spurious phase and resonance amplitude information, which varies in a complicated way with θ and with frequency. No detailed attempt has been made to study the effect of this perturbation analytically, except to note that it is small for magnetic fields greater than about one line width.

The effect of an rf field not exactly perpendicular to H_0 is to introduce, in the above equations, a correction term to M_0 proportional to $(1 + \omega_0^2 T_2^2)^{-1}$. However, it does not change the above results appreciably.

The Bloch-Siegert effect[8] is a well-known effect depending upon higher order perturbation terms involving H_1. It can be obtained in the above formalism by including m_2 and m_{-2} in the closed solution for f_{-1} and gives an apparent decrease in resonant frequency given by

$$\delta\omega = \gamma H_1^2/4H_0.$$

Its effect can be maintained moderately small, although perhaps not negligible, by always maintaining $H_1 \ll H_0$.

To summarize the above results, if the oscillation frequency of the self-oscillator is greater than the line width, then it represents the true Larmor frequency with possible small and known corrections. In a given field (such as 0.5 gauss) these corrections are the smaller the narrower the line width. For fields less than about one line width, however, the oscillation frequency depends in a complicated way on orientation angle and other variables but does not in general become less than the line width. An output frequency close to the line width is therefore suspect unless the exact operating conditions of the instrument are known.

Effects of Line Structure

The hyperfine splitting in the alkali atoms gives rise to an incipient Back–Goudsmit effect, which is manifested as a splitting of the resonance line into $2F + 1$ components, the separation between components depending upon the hyperfine constant and being proportional to H_0^2. It turns out that for virtually all stable alkali isotopes, this splitting is negligible for $H_0 < 0.1$ gauss, but is relatively large at $H_0 = 0.5$ gauss. Table I gives the details of this structure for a field of 0.5 gauss.

Table I. Splitting of the Zeeman Resonance in a Field of 0.5 Gauss[a]

Isotope	Number of lines $2I + 2$	Separation between adjacent lines (cps)	(10^{-5} gauss)	$\gamma_n H_0/\pi$ for $H = 0.5$ (cps)
Na^{23}	5	138	19.8	1126
K^{39}	5	531	76	199
K^{41}	5	1005	144	109
Rb^{85}	7	36	7.7	411
Rb^{87}	5	36	5.2	1393
Cs^{133}	9	6.7	1.9	558

[a] Only the hyperfine level $F = I + J$ is considered here; the $F = I - J$ level usually gives much weaker signals, for reasons that are not entirely clear. The column $\gamma_n H_0/\pi$ gives the separation between the centers of the $(I + J)$ and $(I - J)$ patterns.

In the presence of this structure, the designer of the magnetometer can do one of two things. He can either attempt to operate on only one of the individual components, hoping that the presence of the others will not perturb the operation appreciably, or he may attempt to operate under conditions of a relatively broad line in which case the structure is almost completely submerged under the over-all resonance. Magnetometers designed according to the first principle have been made to operate in the laboratory, but operation by the second method is much to be preferred in most cases, since the line width of a hundred cycles or so is compatible with good signal-to-noise ratio.

The line shape obtained by smearing over an unresolved structure is bound to be unsymmetrical in a rather complicated way, depending on the matrix elements for the various individual transitions and other considerations. However, this asymmetry should invert itself when the magnetic field is reversed in direction, since this is equivalent to interchanging the signs of all magnetic quantum numbers. It is apparent that a single-cell self-oscillating magnetometer in $H_0 = 0.5$ gauss may therefore exhibit a fairly large orientation dependence as θ is varied between 0° and 180°. Fortunately the double-cell self-oscillator magnetometer avoids this situation, as it does many other situations of asymmetry, provided that the sense of circular polarization of the light beams is chosen to be opposite as observed by a single observer (Fig. 5). In this way, the two components of the dual oscillator tend to "pull" themselves together to a common median frequency, which is also the center of symmetry of the two line shapes. The requirement of perfect mirror symmetry, however, requires also that the behavior of the system, i.e., gas cell absorption, photocell efficiency, amplifier gain, etc., be identical in both systems.

V. Response to Rapid Changes in Magnetic Field

One of the interesting characteristics of the self-oscillator magnetometer is its ability to respond to rapid and large excursions in magnetic field value. In general, a freely precessing spin follows faithfully all instantaneous changes in field; questions then arise as to (a) whether these changes can be detected in the output, and (b) whether the effect of the feedback loop has any effect on the instantaneous motion. With regard to the first question, the output will be a faithful representation of the input provided that the amplifiers are of sufficient bandwidth to accommodate all of the various frequency components generated during the frequency excursion. As for the second question, it can again be shown that the feedback loop will remain tightly locked as long as the signals are within the amplifier bandwidths; however, it is not necessary that this be so. As long as the time interval of the excursion is less than the T_2 of the precessing spin system, then the rf in the feedback effectively has no driving force on the spins during this time interval, and the spins are in free precession as if the rf were not there. (For longer excursion times the bandwidth required, which is inversely proportional to the excursion time, is certainly adequate.)

We will now support the statement that the value of the rf field in the feedback loop is never so great as to affect the spin precession in a time less than T_2. The time required for the rf field to interact with the spin system is approximately $(\gamma H_1)^{-1}$. If one attempts to operate the oscillator with $\gamma H_1 T_2 > 1$, one finds that a very undesirable amplitude variation or "squegging" occurs, in which the oscillation alternately builds up and quenches at a rate roughly proportional to H_1. The effect was first observed experimentally and then it was found, on a theoretical basis, that effects of this sort can be expected in all quantum resonance systems involving feedback, as for example in masers. A detailed treatment of the problem has been given by Singer and Wang.[9] It is sufficient to remark here only that the response of the spin system with regard to the feedback loop is similar to that of a spin system in a maser (in which case the feedback loop consists of the radiation reaction inside the cavity). Since the "squegging" is very undesirable, gain controls must be introduced in the magnetometer amplifiers to keep the rf field down to a safe value, and this also automatically eliminated rapid transient perturbations of the rf on the spin system.

A more detailed study of the rapid response characteristics of the magnetometer was made by simulating both single- and double-cell magnetometers on an analog computer. In this study the time development was started with the spins in equilibrium with the driving rf field corresponding to continuous oscillation. A transient was then introduced equivalent to making H_0 first slightly negative and then highly positive in a short time interval. An example of such a run is shown in Fig. 7. It can be seen there that the quantity given by $d\varphi/dt$, where

$$\varphi = \tan^{-1}(M_y/M_x)$$

does indeed represent a faithful description of the instantaneous Larmor frequency. However, if the received information consisted of either M_x or M_y alone, then it might be difficult to resynthesize the exact frequency and phase variations, particularly when the field reverses direction. There is therefore a great advantage in two-phase relative to single-phase output information for this type of situation. In this case, the double gas cell magnetometer has a definite advantage over the single cell magnetometer in that two-phase information is actually available from the outputs of the two photocells.

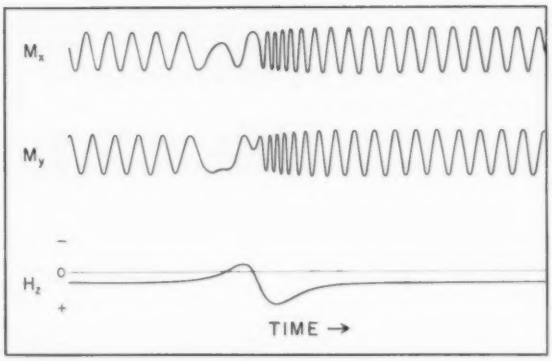

Fig. 7. Analog computer curves showing response of self-oscillator system to relatively large and rapid magnetic field transients.

The above comments pertain to the situation in which the magnetic field transient consists of a vector parallel to the average magnetic field H_0. If this is not the case, then the behavior of the self-oscillator is somewhat more complicated, but to a certain extent, by employing two-phase output, one can obtain some information as to both the magnitude and the direction of the transient. Under severe situations, a transient at right angles to H_0 can quench the oscillations completely, in which case they will require the normal period of $(\gamma H_1)^{-1}$ in which to build up.

VI. Conclusions

Starting from a discussion of optically pumped magnetometers in general, we have concentrated on the two types of self-oscillating rubidium magnetometers represented by the single cell and double cell system. It has been shown that these systems have an intrinsically extremely high signal-to-noise ratio, the possibility of a wide dynamic range, an orientation dependence (with regard to signal-to-noise ratio) which is no worse than other types, and an ability to respond to, and to give data on, extremely rapid field fluctuations. In addition, the double gas cell system has the advantage of a north-south orientation independence, a symmetrized line eliminating possible second-order heading error effects, and the ability to present two-phase information. Magnetometers of both the single and double gas cell types have been flown in space exploration missions and have demonstrated their usefulness. It is expected that these instruments will find increasing use both for outer space and for geophysical explorations.

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Men and Milestones in Optics

I. George Gabriel Stokes

E. Scott Barr

Those great men who laid the foundations on which modern optics has erected its imposing structures are all too often either entirely unknown to their beneficiaries or known only by a name attached to a law or the like. This prevailing unfamiliarity with our scientific ancestors is certainly to our discredit, and it is the hope of the writer that these sketches may be both helpfully informative and intrinsically interesting.

It would be difficult to find a person more suitable to be introduced to the readers of the first issue of *Applied Optics* than Sir George Gabriel Stokes, Baronet, for a wide variety of topics in optics received his attention. In 1849[1] he described his combination of cylindrical lenses which first made possible the determination of the correction needed for visual astigmatism (discovered by his friend G. B. Airy in his own vision about 1825). Three years later he published the famous paper which detailed his penetrating and illuminating study of the nature of fluorescence.[2] Although Ritter is conceded to have been the discoverer of the ultraviolet region, its exploration was largely made possible by the work of Stokes. In connection with his study of fluorescence Stokes introduced the use of quartz lenses and prisms, replaced the Daguerrotype plate by a fluorescent plate, and inaugurated the use of an electric spark as an ultraviolet source. Without question he was one of the first to apply optical methods to chemical analysis,[3] and in the opinion of many (including Lord Kelvin) Stokes was the first (sometime prior to 1852) to comprehend the nature and significance of the Fraunhofer lines in the solar spectrum with reference to spectroscopic analysis. It was characteristic of Stokes that he himself disavowed any priority over Kirchoff and Bunsen,[4] saying that his private conversations and lectures could not take precedence over their published paper. In the field of spectroscopy he did, however, discover that our atmosphere absorbs solar ultraviolet radiation[5] and made the first observations beyond the atmospheric cutoff. The problems of lens design, particularly with respect to telescope objectives, received much attention from him.[6] This interest led him to one of his few collaborative efforts (with Vernon Harcourt), on optical glass composition.[7]

Possibly most important among Stokes' papers on optics is his report on his studies of fluorescence. In this 100-page memoir he described his investigations of the phenomenon observed by Sir John Herschel, who found that, when a beam of sunlight fell on the surface of a sulphate of quinine solution, a blue glow appeared at the surface. Herschel found that light which had produced the glow at one surface could not go on to produce it again at a second surface, and accordingly designated the transmitted light as "epipolized." He offered no explanation of the phenomenon. Stokes repeated and extended the experiment and soon became convinced—on Monday, April 28, 1852, according to his daughter—that what was happening was that light of one wavelength (and thus of one "refrangibility") was being absorbed and light of another wavelength (and another "refrangibility") was being emitted by the illuminated material. In this report appeared his important generalization (Stokes' Law), expressed in these words: "When the refrangibility of light is changed by dispersion it is *always lowered*." Although in this paper he spoke of the process as "internal dispersion," he was dissatisfied with the term, and actually originated the modern word in a footnote which reads: "I am almost inclined to coin a word, and call the appearance *fluorescence*, from fluor-spar, as the analogous term *opalescence* is derived from the name of the mineral."

In this day of complex and elaborate instrumentation it is of interest to learn that Stokes' work on fluorescence was done in a small passageway in his own home, using only a sunlit slit, some prisms (with faces only 34 mm by 40 mm, and apex angles of 24° to 43°) and magnifying glasses (lenses 5.6 mm or 8.6 mm in diameter,

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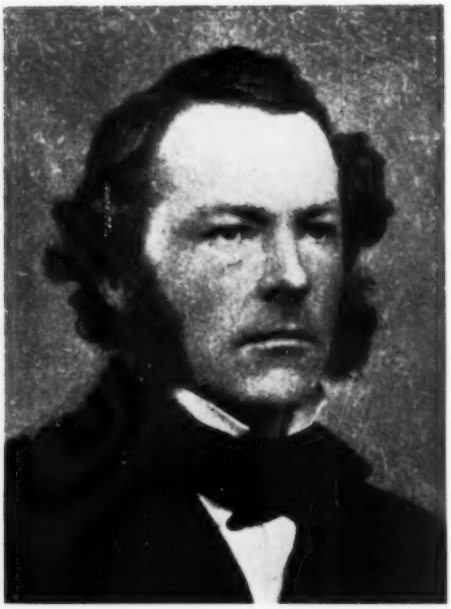

George Gabriel Stokes, 1857. Reproduced from the frontispiece of "Memoir and Scientific Correspondence of the late Sir George Gabriel Stokes, Bart.," Vol 1. Selected and arranged by Joseph Larmor. Cambridge Univ. Press, 1907.

with focal lengths of 19 mm and 13 mm). His results are a real tribute to his skill as an observer.

While Stokes carried out a variety of other investigations and studies in optics—solar radiation, diffraction, interference involving multiple reflection, polarization, double refraction, etc.—he did not limit his activities to optics by any means. For instance, the importance of his work on the viscosity of fluids can hardly be overestimated. His theoretical studies of this topic led, on the one hand, to important papers on ocean waves, and on the other to the equation giving the rate of fall of a droplet of liquid in air[8] which Millikan used in his determination of the charge on the electron. These studies in hydrodynamics also led him to the writing of several important papers in the field of sound. With Stokes experiment and theory almost always went hand in hand and, as P. G. Tait put it, "few men have ever had so small a percentage of *barren* work, whether mathematical or experimental, as Stokes." The justly famous J. J. Thomson paid him an equally high tribute when he said, "In Stokes there is that rare but effective combination of the highest mathematical powers and the greatest experimental skill . . . With simple apparatus . . . he has solved some of the most crucial questions in physical optics."

While Stokes may certainly with propriety be considered a physicist, his actual title was Lucasian Professor of Mathematics, a title which was more than justified by his numerous valuable mathematical papers. As if all the foregoing were not enough, Stokes demonstrated in his papers an obvious competency in both botany and chemistry. As a matter of fact, he was once described as "a professor of mathematics who used physical methods to make fundamental discoveries in biochemistry."

Stokes was born at Skreen, County Sligo, Ireland, on August 13, 1819 (the same year as Fizeau and Foucault). His ancestors were notably clerical—his father and both of his grandfathers were Church of England rectors; Stokes himself married the daughter of another Episcopalian clergyman. He was the youngest of eight children and spent his childhood in that remote village which was visited by neither vessels nor coaches—but where ". . . chickens cost sixpence and eggs were to be bought at the rate of five or six a penny," to quote his daughter, Mrs. Lawrence Humphry.[9] The simple village life endowed him with a strong physique and lifelong good health (except for a bout with smallpox as a child).

After some early education at home, Stokes was sent to school in Dublin, and was there when his father died suddenly when he was fifteen. As a youth Stokes was interested in biology and his daughter reports that " . . . one day . . . returning from a walk, he failed to respond to the salutation of some ladies of his acquaintance; when asked the reason for such odd behaviour he answered that he could not bow, as his hat was full of beetles."

In 1837 he went to Pembroke College at Cambridge University, where he remained almost continuously for 66 years. He had no interest in sports while in college or later, but got his exercise by taking long "grinds" along country roads at a four miles an hour pace. He continued this practice all his life, and at 83 was still taking walks of three or four miles.

After receiving his M.A. degree in 1841 he was elected a fellow of Pembroke College and remained there to teach privately. He held this position until he was disqualified as a result of his marriage on July 4, 1857. He was reinstated in 1869 following a revision of the college rules and held the post from then until 1902, when he was made Master of the College. In 1849 he received the high honor of being designated Lucasian Professor (a chair endowed by E. Lucas in 1662) and continued as such until his death.

According to Lord Kelvin, "the first physical laboratory in European universities—certainly in England—was in the rooms used by Stokes in 1840–43." His technical writings began with a paper in 1842 and during the next ten years he published about fifty. In all he published some 140 papers, only three or four

of them being collaborative. They range in length from one of only 21 lines (in 1872) to long articles of a hundred pages or so. His collected papers fill five volumes (three edited by him and two by Joseph Larmor, who followed him as Lucasian Professor). His correspondence fills two more volumes. The quantity of his papers was not at the expense of quality, and as Theodore Lyman says in his *Spectroscopy of the Extreme Ultraviolet*, "His papers are of such importance that the reader cannot do better than to consult them in the original."

In 1851 he was made a fellow of the Royal Society of London and in 1854 became its Secretary. He held that post for thirty-one years and was then President from 1885 until 1890.

Stokes proved to be a conscientious and able Secretary, particularly with respect to his duties as editor of the publications of the Society. His editorial supervision prevented the publication of many errors (he once rejected a paper by Faraday—who admitted that Stokes was right) and his helpful suggestions did much to improve the quality of the work reported by others. His ingenuity, breadth and depth of knowledge, and catholicity of interests resulted in his being an invisible collaborator on many important papers. The quantity and quality of his suggestions and criticisms can only be appreciated by a perusal of his correspondence.[9] The number of famous and able workers who sought his aid (and the extent to which it was gladly given) is surprising: among the more than sixty persons represented in the Larmor collection are Airy, Clerk Maxwell, Cornu, Crookes, Faraday, Haidinger, Joule, Kelvin, Langley, Poggendorff, Tait, and Vernon Harcourt, to mention only a few. The subjects of the letters run the gamut from discussions of theory with Clerk Maxwell to practical suggestions to the great optician, Adam Hilger. As Smithells put it, "This advice was as valuable as it was profuse . . . What Stokes did for his generation can hardly be estimated."

As Stokes admitted, he "gave up an immense amount of time to the improvement of hopeful work," and his own output naturally dropped. However, it appears that the advancement of science profited on the whole. Sir William Crookes wrote, after looking over his correspondence with Stokes, that the letters "serve to show the enormous indebtedness I, in common with most scientific men who correspond with him, owe to Stokes. . . . the impression they leave on my mind is that I knew very little of the subject in question, and if what I owe to Stokes is deducted from my work there will be precious little left I can claim for my own!" Typical, too, is the statement by Lord Kelvin that "for sixty years of my own life, from 1843 to 1903, I looked up to Stokes as my teacher, guide, and friend."

Stokes took his teaching duties equally seriously, and was greatly concerned with the quality of his lectures. He has been described as an excellent lecturer and a splendid demonstrator. Many of his discoveries were disclosed in his lectures without their ever being published (and others appeared merely as notes to the papers of others). Time had apparently little importance to him, for one of his "hour" classes lasted from noon until 2:30 and it is said that he once gave a lecture on hydrodynamics which lasted from 12:15 until 3:05—for one student, Barkla! He devoted much care to the preparation and administration of competitive examinations, and the famous Stokes' Theorem (concerning the transformation of a line integral into a surface integral) appeared on one of his examinations simply as a theorem to be proven. The list of notable men who were students under him is a truly distinguished one.

To Stokes' great intellectual gifts was added an equally admirable disposition. He was remarkable for his openness and his simplicity of manner, and was so far above the petty jealousies of life that he was apparently entirely unconscious of their existence. His daughter wrote that "He seldom gave opinions upon the characters of persons, and only when asked to do so," and "It was rarely that unkind and unjust things were said before him; inaccurate people became more exact in his presence." His most notable trait was probably his ability—or more accurately his inclination—to remain silent. Having been warned as a youth by one of his brothers not to give "long Irish

George Gabriel Stokes. Reproduced from the portrait accompanying the obituary notice in Proc. Roy. Soc. (London) **75,** facing p. 199 (1905).

answers," he went to the other extreme to some extent. He would frequently respond with a simple "yes" or "no" when considerably more might reasonably have been expected. Despite his unusually quiet and silent disposition (he once sat by the fireside with a visitor for two hours without saying a word), he did not like to be alone. Consequently he seldom declined any invitations, even those to formal dinners and public functions.

He was described by his daughter in these words: "In stature he was rather short than tall, firmly and strongly knit, strong rather than graceful in person, his head very large but so well moulded and proportioned that it did not seem too large for his height, very finely shaped over the forehead, with a splendid sweep of brow; the eyes rather small than large, of a gray blue tone and bright; his complexion clear and slightly ruddy, giving an impression of health."

While he knew Latin, Greek, German, French, and Italian quite well, Stokes seems to have had little interest in literature and to have done relatively little reading that was not professional or theological. His greatest aesthetic interest appears to have been centered on colors, and he was quite regular in his visits to exhibits of painting.

Stokes' daily routine was somewhat unusual in that he generally ate only breakfast (at 9 o'clock) and dinner (at 5 o'clock). He hardly ever ate lunch until he was eighty, and then only under protest. His dinner included two glasses of beer, and a glass of port for dessert. He usually went to bed about one o'clock, but frequently stayed up until two-thirty or three. These late hours did him no harm, for he made use of his gift of being able to nap soundly at any and every opportunity, and awake refreshed and fully alert.

Stokes' happy marriage was blessed by two sons and a daughter. (His older son, George, 1863–1942, was well known for his work on steam turbines and dynamos.) In her later years Mrs. Stokes became something of an invalid and died on December 30, 1899, a little more than three years before him.

While life at the Stokes' home was generally happy, he seems to have been rather trying in some ways. His daughter wrote with some feeling "He had two really wicked characteristics, that he would never allow anyone to help him with his work, not even permitting invitations to be answered for him, and that he kept every single thing he received by post, even advertisements. His study was enough to drive any house maid 'wild.' He used gradually to acquire tables from the rest of the house, until there were as many tables as the room would hold, with narrow passages between, through which to squeeze if one could. On these tables papers were piled a foot or more deep. It may be imagined that, keeping everything, he could 'find nothing.'"

Stokes' real shortcomings were few. He was inclined to be indecisive over trifles, but possibly overcaution was his greatest fault. He was hesitant both with regard to drawing conclusions and to publication of results, although actually his work was almost always in the right direction, being guided both by accurate experimentation and by a sure instinct. "There was a substratum of inertia and procrastination which he always fought against," according to his daughter. While he was meticulous with respect to all duties, even when they were more or less formalities, many of his friends felt that he had a tendency to give priority to matters with deadlines, to the neglect of more important things which were unscheduled—as, for instance, the delaying of the third volume of his collected works for eighteen years after the appearance of the second, and fifty years after publication of the papers contained in it.

During his long life Stokes received almost every honor which could come to a scientist. Eight honorary doctorates were awarded to him, and seven medals—Rumford (1852), Haidinger (1856); Gauss (1877), Copley (1893); Wilde (1897); Argo (1899); and Helmholtz (1901). He was President of the British Association for the Advancement of Science in 1869, and was made a baronet on July 6, 1889. It has been said that Stokes patterned his life after that of Newton. If so, he was more than successful: he and Newton held the same three high offices—Lucasian Professor, President of the Royal Society, and Member of Parliament for Cambridge University (1887–1891)—with one difference in that Stokes held them simultaneously, which Newton did not. They did, however, have in common the fact that neither made a speech in Parliament. Two hundred years separated their terms in Parliament, and Stokes was the first scientific man to represent Cambridge after Newton. A memorial medallion of Stokes was placed in Westminister Abbey in 1904.

Stokes seems to have had the liking of all and the friendship of many. Closest to him were probably Rayleigh, Henri Becquerel, Kelvin, and Clerk Maxwell. The 1899 jubilee in celebration of his appointment as Lucasian Professor in 1849 was attended by notables from all over the world, and tributes in great number came from learned societies, universities, and individuals.

Stokes' interests as a churchman and theologian remained strong throughout his life and were evident at times in his writings. With advancing years he devoted an increasing amount of time to religious matters. Until shortly before his death his faculties remained unimpaired and he continued to be interested in scientific advances until his last brief illness before dying at the age of 83 on February 1, 1903, at Cambridge. His obituary in the *Proceedings of the Royal*

Society [**75,** 199 (1905)] was written by Rayleigh.

Two small comments remain. Stokes' poor handwriting became progressively worse until it was almost illegible, which resulted in his being the first man at Cambridge to use a typewriter—to the relief of his correspondents. Finally, it may be of interest to mention the fact that his chemical and biological investigations may have been facilitated by the fact that he had no sense of smell—as evidenced by his unawareness of a deceased family of mice under the floor at his home, and his keeping "for ages" soup bowls of animal blood beside his writing desk at the time he made his spectral studies of blood.

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One original and one carbon of the manuscript, with two sets of all illustrations, must be sent. Manuscripts should be typed double or triple spaced on one side of 22 × 28 cm ($8^1/_2$ × 11 in.) paper, leaving a 3.8 cm ($1^1/_2$ in.) margin all round.

An **abstract,** adequate as an index and summary, of not more than 100 words should appear at the beginning of the paper after the *title, author's name, affiliation, and address.* In the case of papers in a non-English language, they must be accompanied by an abstract in English as well as an abstract in the language of the paper.

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1. F. C. Brown, Phys. Rev. **28,** 825 (1821).
2. J. Culpeper, *Space Optics* (Georgetown Institute of Technology Press, Washington, D.C., 1861) pp. 298, 345.

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No **galley proofs** will be sent to authors; all proof reading will be done in the house. Therefore, an author will not see his paper from the time it is accepted and any alterations agreed between Editor and Author, until it appears in print.

Letters to the Editor should follow the above suggestions, but no abstract is required.

Meetings Calendar

1962

January

10–12 10th Southeastern Seminar on Spectroscopy *Wm. T. Tiffin, University of Florida*

11 Joint Meeting OSA Rochester Section and Society of Photographic Scientists and Engineers *J. L. Rood, Bausch & Lomb, Inc., Rochester, N.Y.*

15–17 Optical Character Recognition Symposium, Washington, D.C. *Josephine Leno, Code 430A, Washington, D.C.*

22–24 Institute of Aerospace Sciences 30th Annual Meeting, New York *IAS, 2 E. 64th St., New York 21, N.Y.*

23 OSA Rochester Section *J. L. Rood, Bausch & Lomb, Inc., Rochester, N.Y.*

24–27 American Physical Society, New York *K. K. Darrow, 538 W. 120th St., New York 27, N.Y.*

28–Feb. 3 Pan American Association of Ophthalmology, Lima *J. Valdeavellano, 810 Avenue President Wilson, Paris, France*

29–Feb. 16 World Meteorological Organization Commission for Instruments and Methods of Observation, New Delhi *41 avenue G. Motta, Geneva, Switzerland*

February

6 OSA Rochester Section *J. L. Rood, Bausch & Lomb, Inc., Rochester, N.Y.*

6 Society for Applied Spectroscopy New York Section —Accessory Equipment papers

14–16 International Solid State Circuits Conference, IRE, Univ. of Pa. *R. B. Adler Rm. C-237, MIT Lincoln Lab., Lexington, Mass.*

16–17 Society for Applied Spectroscopy, Idaho Falls *G. V. Wheeler, Phillips Petroleum Company, Post Box 2067, Idaho Falls, Idaho*

19–21 Range Reconnaissance and Tracking of Aerospace Vehicles, San Francisco *IAS, 2 E. 64th St., New York 21, N.Y.*

20 OSA Rochester Section meeting on optical character recognition *J. L. Rood, Bausch and Lomb, Inc., Rochester, N.Y.*

March

1–3 8th Scintillation and Semiconductor Counter Symposium, Hotel Shoreham, Washington, D.C. *G. A. Morton, RCA Labs, Princeton, N.J.*

5–9 13th Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy, Penn-Sheraton Hotel *L. P. Melnich, U.S. Steel Corp., Monroeville, Pa.*

14–17 **Optical Society of America Spring Meeting, Mayflower Hotel, Washington, D.C.** *K. Kessler, National Bureau of Standards, Washington, D.C.*

— American Society for Photogrammetry, Shoreham Hotel, Washington, D.C.

20 OSA Rochester Section Joint Meeting with American Chemical Society *J. L. Rood, Bausch & Lomb, Inc., Rochester, N.Y.*

26–29 IRE International Convention, New York *D. B. Sinclair, IRE H.Q. 1 E. 79th St., New York 21, N.Y.*

26–29 Instrument Society of America Meeting, Dallas *W. H. Kushnick, 312 6th Ave., Pittsburgh 27, Pa.*

28–31 Molecular Spectroscopy Conference, London *Institute of Petroleum, 61 New Cavendish St., London, W.1, England*

April

— American Astronomical Society Meeting, Cambridge, Mass.

— Symposium on the Optical Maser, New York *E. Weber, Polytechnic Institute of Brooklyn, New York*

— Association for Applied Solar Energy Symposium on Solar Science, Phoenix, Ariz.

2–13 8th Munich Photogrammetry Week *H. Bischoff, Zeiss-Aerotopograph G.M.P.H., Ismaningerstrasse 57, Munich 27, Germany*

3 OSA Rochester Section Meeting *J. L. Rood, Bausch & Lomb, Inc., Rochester, N.Y.*

3 Society for Applied Spectroscopy New York Section Atomic Absorption Spectroscopy Meeting, Statler-Hilton Hotel, New York

13–14 APS New York Section Symposium on Plasma Physics, Tarrytown, N.Y. *A. F. Turner, Bausch & Lomb, Inc., Rochester, N.Y.*

16–19 1st International Conference on Vacuum Ultraviolet Radiation Physics, Univ. So. Calif. *G. L. Weissler, Univ. So. Calif., Los Angeles 7, Calif.*

17 OSA Rochester Section, OSA President's Address *J. L. Rood, Bausch & Lomb, Inc., Rochester, N.Y.*

23–26 American Physical Society, Washington, D.C. Meeting *K. K. Darrow, 538 W. 120th St., New York 27, N.Y.*

30–May 3 SMPTE Semi-Annual Convention, Los Angeles, Calif.

30–May 3 13th Annual Mid-American Symposium, Society of Applied Spectroscopy, Hotel Conrad Hilton, Chicago, Ill. *Fr. Devlin, Boston College, Chestnut Hill, Mass.*

May

— IRE International Scientific Radio Union, Washington, D.C., Spring Meeting *IRE, 1 E. 79th St., New York 21, N.Y.*

6–10 Electrochemical Society Meeting, Statler Hilton Hotel, Los Angeles, Calif.

7–11 Society of Photographic Scientists and Engineers, Somerset Hotel, Boston, Mass. *K. Kohlman, 13712 Mariana Dr., Rockville, Md.*

8 OSA Rochester Section Annual Dinner Meeting *J. L. Rood, Bausch & Lomb, Inc., Rochester, N.Y.*

8 Society for Applied Spectroscopy New York and Philadelphia Sections Solid State Lasers Meeting

20–23 Radiation Research Society 10th Annual Meeting, Colorado Springs

21–25 Max Planck Institute for the Advancement of Science, 13th General Assembly, Düsseldorf *J. Ammundsen, Sammenslutningen of Arbejdsgindere Indenfor den Keramiske Industri, Norrevolgade 34, Copenhagen, Denmark*

22–24 IRE National Microwave Theory and Techniques Symposium, Boulder, Colo. *R. W. Beatty, NBS, Boulder, Colo.*

28–June 2 International Optical League Berlin Congress *G. H. Giles, IOL, 65 Brook St., London, W.1, England*

29–June 19 World Meteorological Organization, Geneva, Switzerland

31–June 3 German Bunsen Society for Physical Chemistry 61st General Assembly, Münster, Germany *Carl Bosch Haus, Varrentrappstr, 40–42, Frankfurt am Main, Germany*

31–June 7 International Television Conference London *Institution of Electrical Engineers, Savoy Place, London, W.C.2, England*

late Interphoto Congress, Copenhagen *International Photography and Cinematography Dealers Association, Steienvorstadt 63, Basel 10, Switzerland*

late Washington Symposium on Use of Artificial Satellites for Geodetic Purposes *International Association of Geodesy, 18 rue Auber, Paris IX, France*

June

7–10 Canadian Association of Physicists 17th Annual Congress, Hamilton, Ontario

11–14 Instrument Society of America Seattle, Wash., Instrument-Automation Conference and Exhibit *W. H. Kushnick, 313 6th Ave., Pittsburgh 22, Pa.*

11–15 Columbus Symposium on Molecular Structure and Spectroscopy *R. A. Oetjen, Dept. Physics, Ohio State University, Columbus 10, Ohio*

18–22 Eindhoven Congress on Magnetic and Electric Resonance and Relaxation *D. J. Kroon, Natuurkundig Laboratorium, N.V. Philips' Gloelampenfabriek, Eindhoven, Netherlands*

18–22 International Conference on Spectroscopy, Univ. of Maryland *B. F. Scribner, National Bureau of Standards, Washington 25, D.C.*

24–29 ASTM National Meeting and Apparatus Exhibit, Statler Hotel, New York *ASTM, 1916 Race St., Philadelphia 3, Pa.*

A Rotating-Sector Attenuator of Adjustable Transmittance for Precise Spectrophotometry

James E. Stewart

A rotating-sector attenuator has been constructed using components of readily available precision. The transmittance of the attenuator is adjustable in motion through a differential gear system and can be read from a dial with a precision of about ±0.02% of maximum transmittance. The sector has been used to measure and calibrate the photometric properties of spectrophotometers in the ultraviolet, visible, and infrared regions. It has also been used as an attenuator in an optical-null infrared spectrophotometer in place of the usual comb. Absorption spectra of typical samples have been made with a precision of ±0.04% transmittance. Transmittance and absorptivity data are presented for samples of calcium fluoride in the 700 to 1300 cm^{-1} spectral region.

Introduction

The use of sector disks, rotated at sufficiently high speed to insure the validity of Talbot's law, is well known in spectrophotometry.[1,2] A useful arrangement comprises two disks mounted concentrically with provision for adjusting their phases in order to provide some control over the transmittance. Sectors of this type have been devised which can be adjusted while in motion[3,4] either by various mechanical means or by varying the phase of driving motors. Such devices have been used as optical attenuators for actual[5] or proposed[6,7] spectrophotometers, but many of them suffer from deficiencies in convenience, accuracy, or noise due to random or systematic fluctuations in transmittance. The sectors used by Kortüm[3] are unquestionably the best which have been available. However, their construction requires very exact (and therefore, very costly) machining. Transmittance is read from a finely divided scale on the disks using a stroboscopic light.

Principle of the Rotating-Sector

It was desired to construct a two-disk rotating sector of modest cost using components of readily available precision. A chopping frequency of 360/sec is required with the speed of rotation of the disks to be limited to no more than 30 rps. The precision requirements are severe. Accuracy, repeatability, and noise are not to exceed the limit set by the fineness of the servo and recorder potentiometers of modern spectrophotometers, usually an amount corresponding to about 0.05% transmittance. For two sector disks of twelve blades each this amounts to an error in relative phase angle of about 27 sec of arc.

The instrument which was developed is based on a principle sketched in Fig. 1. A gear, G_1, attached to the rotating shaft R, drives G_2. Gear G_3, which is fixed on the same shaft S as G_2, in turn drives G_4. G_4, on which a sector disk, D, is mounted, is supported by, but not fixed to, the shaft R. A similar gear train (G_1', G_2', G_3', G_4') drives a second sector disk, D'. If the numbers of teeth on the gears are such that $N_1 = N_3 \neq N_2 = N_4$, then the speed, Ω_4, of G_4 is

$$\Omega_4 = N_2N_1\Omega_1/N_2N_4 = (N_1/N_2)^2\,\Omega_1$$

Now imagine what happens when shaft S' is rotated once about R, with R and G_1' held stationary. This is equivalent to a rotation of S' about R with G_1' and G_4' rotating about R at the same rate, followed by a rotation of G_1' in the reverse direction with S' stationary. As one rotation of G_1' produces $(N_1/N_2)^2$ rotations of G_4', the rotation of shaft S' about R produces $(N_1/N_2)^2 - 1$ rotations of G_4' relative to G_1'. This amounts to about 7.46° for a choice of gears having $N_1 = 95$ and $N_2 = 96$ teeth. A twelve-bladed disk must advance 15° relative to its partner to cover a complete range of zero to fifty percent transmittance. This is accomplished by about 720° of rotation of S' about R. Transmittance settings repeatable to 0.05% require only that the angle of rotation of S' can be set to within about 22 min of arc.

It is necessary to consider how construction errors

The author is at Beckman Instruments, Inc., Fullerton, Calif.

Received 10 May 1961.

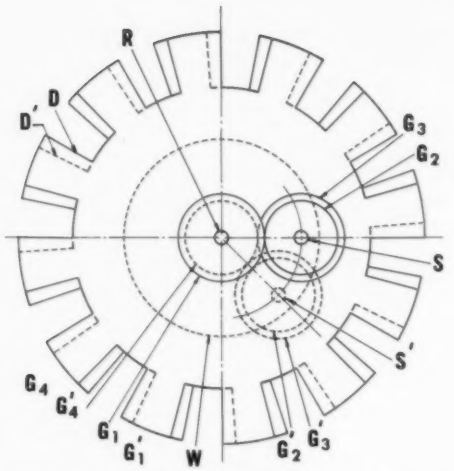

Fig. 1. Schematic drawing of rotating-sector attenuator.

can influence the nominally linear relationship between the rotation of S′ about R and the phase difference between the disks. Eccentricity in G_3, G_4, G_3', and G_4' will produce a relative motion of the blades of the same frequency as the rotation speed. This means that successive exposures between blades will be of different duration, but this effect will be canceled by the integrating action of the device except for very narrow openings. Eccentricity in G_1, G_2, G_1', and G_2' will produce a relative motion of the blades of considerably lower frequency Ω_e, given by

$$\Omega_e = [1 - (N_1/N_2)^2]\Omega_1.$$

In the case chosen ($N_1 = 95$, $N_2 = 96$, and $\Omega_1 = 30$ cps) Ω_e has the value 0.62 cps. So-called "precision 3" gears are readily available with a maximum total composite error of 0.0063 mm. Hence the amplitude of the low frequency error can be at most $\pm 0.025\%$ transmittance per disk using gears 5 cm in diameter. The oscillations of two disks can cancel or add depending on orientation, and this will depend on the rotation of S′ about R. The readability of the mean value of an oscillating pen line is certainly less than the amplitude. Hence a maximum uncertainty due to this cause should amount to no more than $\pm 0.025\%$ transmittance.

A rotating-sector was constructed with twelve-bladed disks 23 cm in diameter. Precision 3 gears having $N_1 = 95$ and $N_2 = 96$ teeth and precision shafts and bearings were used. A divided dial and vernier readable to 6′ is used to read the rotation of S′ about R. A knurled wheel, W, on which S′ is mounted can be rotated by hand through a friction drive contacting the edge of the wheel. It can also be rotated at a uniform rate by means of a synchronous motor driving through a gear mounted on the wheel. The disks are rotated through a timing belt by a $^1/_{25}$ hp, 1800 rpm Bodine synchronous motor.

For photometric measurements it is not necessary to know the actual transmittance of the sector as only relative values are required. However, it is necessary to insure that the separate openings close to zero simultaneously. This has been accomplished by providing adjustable edges on the blades and a fixture for their alignment. This adjustment also eliminates centering errors.[8] The edges of the blades are offset and tapered in order that they meet in a single plane to avoid vignetting.

Performance and Use

The performance of the rotating-sector was first studied in a Beckman IR-7 Infrared Spectrophotometer. Repeat settings measured with a tenfold expanded scale were made with a probable error of $\pm 0.013\%$ transmittance. The sector has since been used to measure the photometric accuracy of a variety of instruments in the infrared, visible, and ultraviolet spectral regions.

The use of the sector is not limited to photometric calibration of spectrophotometers. It can be used directly as the optical attenuator in double-beam optical-null instruments. As a demonstration of this application the sector was installed in the reference beam of an IR-7. The usual attenuating comb was removed from the instrument and a fine screen was inserted in the sample beam far from a slit image to compensate for the initial fifty percent energy attenuation by the sector. A galvanometer was used to detect the error signal at the synchronous demodulator. In use, the sample and reference beams are equalized by adjusting the sector for zero galvanometer deflection. Transmittance measurements which require two settings of the sector (with and without the sample) have been made with a precision (probable error) of $\pm 0.04\%$ transmittance.

Common sources of error in infrared photometry are thermal radiation by the attenuator, sample, and reference materials and reflection by these elements of radiant energy originating elsewhere. It was found that an uncertainty in the zero setting of an infrared instrument due to these factors could amount to one or two-tenths percent transmittance in the rock salt region (2–15 μ) and could presumably be considerably worse in the far infrared. This error has been eliminated, but at the expense of some energy, by substituting a nonchopping beam splitter element in place of the beam-combining rotating mirror usually used in double-beam infrared instruments. With this modification, the use of the rotating-sector attenuator provides photometric accuracy limited only by the effects of finite resolution and the presence of stray radiation.

Infrared Absorption Spectrum of Calcium Fluoride

Because of their usefulness as transmittance standards in infrared spectrophotometry, the absorption spectra of a number of polished calcium fluoride crystals were measured in the manner described above. Transmittances and absorptivities of three of these plates (Harshaw material) are shown in Figs. 2 and 3. Absorptivities have been corrected for surface reflectivity, calculated from the refractive indices.[9,10] The linear relationship between frequency and the logarithm of the absorptivity was first pointed out by Kaye.[11]

The absorptivities of different fluorite plates are found to differ slightly at higher frequencies, due probably to small differences in scatter and reflection depending on surface condition. There is also some evidence that absorptivities of fluorite samples from different batches differ slightly at lower frequencies, perhaps due to impurities.

The sensitivity of the absorbence of fluorite to changes in temperature was studied over a temperature range from 300° to 380°K. It was found that the absorbence increases by about one-half percent for an increase in temperature of one degree centigrade.

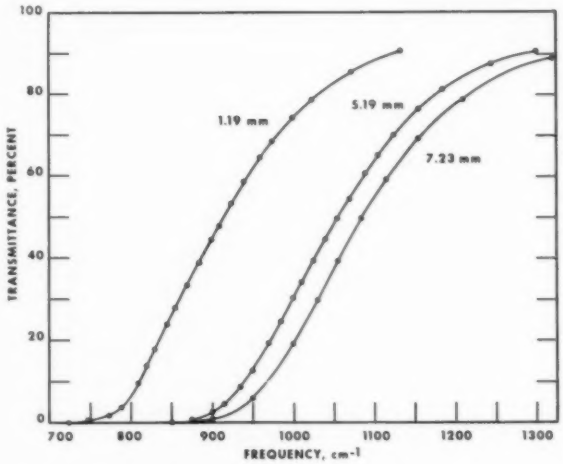

Fig. 2. Infrared transmittance of calcium fluoride, measured with Beckman IR-7 spectrophotometer using rotating-sector optical attenuator.

The author gratefully acknowledges helpful discussions with W. I. Kaye, W. S. Gallaway, and J. Ashley and the contributions of C. Washburn who constructed the rotating-sector and suggested numerous improvements in its design.

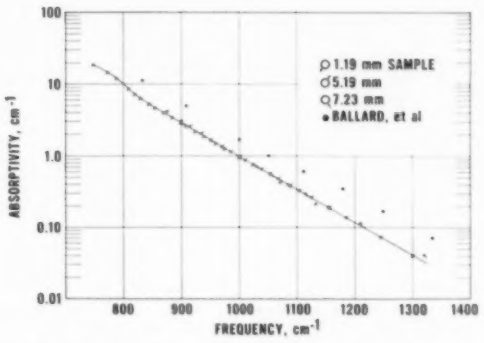

Fig. 3. Absorptivities of calcium fluoride plates at 29°C. The data of Ballard are taken from "The Optical and Other Physical Properties of Infrared Optical Materials," p. 61, final report for ERDL Contract W-44-009 eng-473, 1949, quoted in American Institute of Physics Handbook, pp. 6-37.

References

1. J. W. T. Walsh, *Photometry* (Constable, London, 1953), 2nd ed.
2. G. Kortüm, *Kolorimetrie, Photometrie, und Spektrometrie* (Springer-Verlag, Berlin, 1955).
3. G. Kortüm, Z. Instrumentenk. **54,** 373 (1934).
4. A. Bayle, Rev. opt. **27,** 314 (1948).
5. C. W. Keuffel, J. Opt. Soc. Am. **11,** 403 (1925).
6. R. A. Oetjen and L. C. Roess, J. Opt. Soc. Am. **41,** 203 (1951).
7. H. M. Richardson, R. G. Fowler, and M. L. Coffman, J. Opt. Soc. Am. **43,** 873 (1953).
8. A. F. A. Harper and A. J. Mortlock, Brit. J. Appl. Phys. **4,** 220 (1953).
9. Data of Langley, Paschen, and Rubens given by Coblentz, J. Opt. Soc. Am. **4,** 432 (1920).
10. Ramadier-Delbes, J. phys. radium **11,** 622 (1950).
11. W. I. Kaye, private communication.

Applied Optics

Letters to the Editor

Letters to the Editor should be addressed to the Editor, APPLIED OPTICS, 1155 16th St. N.W., Washington 6, D.C.

A General-Purpose Infrared Lens

Rubin Gelles

Kollsman Instrument Corporation, Elmhurst, New York.
Received 20 July 1961.

The continuing development of infrared applications has led to a requirement for well-corrected objectives which reflective systems do not always satisfy. To meet this need, doublets have been designed using such materials as silicon–germanium, and arsenic trisulfide–lithium fluoride.[1,2] Such combinations have been well suited for use in the spectral region from 3 to 5 μ, where there is an atmospheric window. However, most of these materials are not useful at longer wavelengths, particularly in the 8–12 μ atmospheric window. In this spectral region there is a general lack of materials both optically and mechanically suitable for well-corrected objectives.

In an attempt to find a solution to this problem, it was noted that the dispersion of germanium in the 8–12 μ region is unusually low. Over this 4 μ interval, the difference in index of refraction is only 0.0033, so that the reciprocal dispersion, V, is greater than 900.[3] For a thin lens of germanium, the longitudinal chromatic aberration would be only about one thousandth of the focal length. Although this would be fairly satisfactory with respect to color, the aberrations of a simple lens would necessitate a restricted aperture, whereas aperture ratios between $f/1$ and $f/2$ are frequently required.

However, this problem is readily solved by constructing a two-element, air-spaced objective. The degrees of freedom at the disposal of the designer permit correction of spherical aberration and coma, while the low dispersion is relied on to keep chromatic aberration within bounds. An objective, designed along these lines, is shown in Fig. 1, together with the constructional data for an effective focal length of 10 and an aperture ratio of $f/2$.

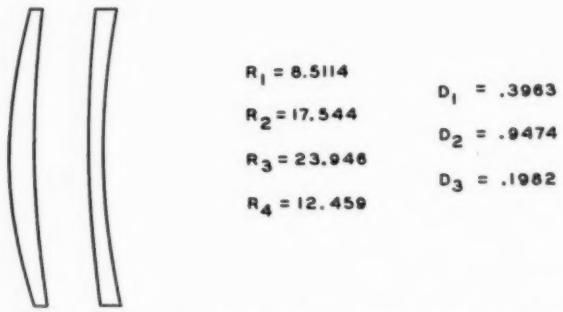

Fig. 1. Constructional data for the two-element $f/2$ germanium lens with a focal length of 10. R is the radius of curvature, and d the axial thickness.

The available degrees of freedom have been utilized to achieve an aplanatic lens in which the aberrations are well controlled. Incidence height vs final axial intercept distance has been plotted for various wavelengths (see Fig. 2). It can be seen that longitudinal spherical aberration is practically nonexistent over a broad range of wavelengths. Although coma is well within the tolerance described by Conrady,[4] the usual undercorrected curvature of field for this type of lens limits the useful field of view. Nevertheless, the blur circle remains less than one milliradian up to two degrees off-axis.

Figure 2 shows that, while there is no control over longitudinal chromatic aberration, the color spread in the 8–12 μ region is

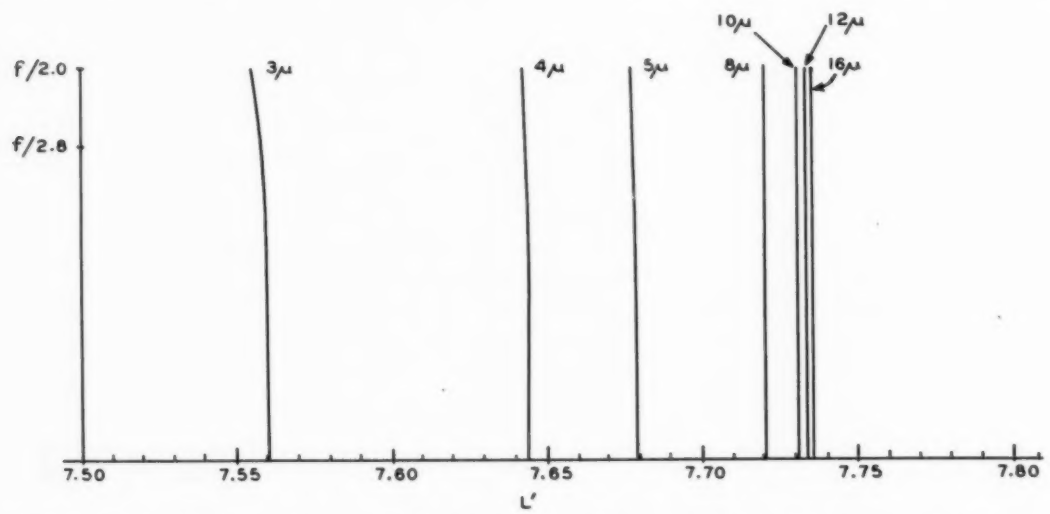

Fig. 2. The final axial intercept distance vs. ray height plotted for the germanium lens with a focal length of 10. The curves show the effect of chromatic aberration from 3 to 16 μ.

only about 0.1% of the focal length. The resulting geometrical circle of least confusion on axis subtends 0.2 milliradian, which is considered acceptable for this type of lens. As expected, chromatic aberration increases at the shorter wavelengths in accordance with the increasing dispersion of material.

The fact that correction of spherical aberration and coma is maintained over a broad spectral range makes the lens particularly attractive as a collimator for an infrared optical bench, where the inevitable central masking in a reflective system would be undesirable. In such an application, a set of narrow-band filters in combination with the lens could be used to select any desired portion of the infrared spectrum.

References

1. R. G. Treuting, J. Opt. Soc. Am. **51**, 454 (1951).
2. E. H. Thielens, U.S. Patent 2,863,253, Dec. 23, 1958.
3. S. S. Ballard, K. A. McCarthy, and W. L. Wolfe, *Optical Materials for Infrared Instrumentation* (Univ. of Michigan, Willow Run Laboratories, Ann Arbor, January 1959).
4. A. E. Conrady, *Applied Optics and Optical Design* (Dover, New York, 1957), Vol. I, Chap. 7, p. 393.

Applied Optics BOOKS

Books for review should be submitted to the Managing Editor, APPLIED OPTICS, 1155 16th St., N.W., Washington 6, D.C.

Elements of Maser Theory. By A. A. Vuylsteke. Van Nostrand, Princeton, New Jersey, 1960. 362 pp. $9.50.

It is now ten years since the invention of the maser by C. H. Townes. The growth of the bibliography in this field has been very rapid and is similar to the process of stimulated emission after which the maser is named. For this reason, books providing a summary and clarification of the periodical literature are much needed.

The volume under review is by far the largest of the published text books or review articles on masers though, to be sure, only about one third of its 362 pages deal with masers as such. The author gives reasonably self-contained accounts of atomic structure, statistical mechanics, electromagnetic theory, and quantum mechanics in a form well adapted to his main purpose. This material could be read easily, and with profit, by a well-trained graduate student in physics. To save space, the author has adopted a fairly formal approach, and it will be interesting to learn how well the book will serve as an introduction to these subjects for students with an electrical engineering background who want to enter the new field of quantum electronics but who for one reason or another have not followed the regular physics curriculum.

Among the topics discussed are the two level pulsed maser, the ammonia beam maser, and three level masers. Term splitting in paramagnetic crystals is given an elementary treatment with further details contained in an appendix. The maser theory is formulated in density matrix notation, which has already been put to good use in the chapter on statistical mechanics for a discussion of nonequilibrium problems. The last chapter contains a discussion of maser noise. A useful bibliography covering publications as late as 1959 and an index complete the book.

In general, the author's discussion of maser theory is a synthesis of material appearing in the literature. In most cases he has taken the best and most fundamental treatments available, but many of the deficiencies of the periodical literature are mirrored in his book. This is particularly true of the discussion of maser noise. The theory of maser operation is not accompanied by any comparison with experimental results, and the simplifications assumed in the calculations usually prevent more than a qualitative agreement in any case. No attempt has been made to deal with infrared or optical masers, but of course these had not been brought to practical realization when the book was written. Despite the fact that there is not a great deal of original material in the book, it will be found useful in this growing field of great practical importance.

W. E. Lamb, Jr.

Infrared Physics—An International Research Journal. Editors: W. K. Weihe, S. Passman, M. Migeotte, and T. S. Moss. Pergamon Press, Oxford and New York.* Per year: $20.00 libraries, $10.00 individuals.

After considerable birth pain, the first issue of *Infrared Physics* (March 1961) has appeared. If one may judge the future by a first issue, this journal will be a valuable contribution to those people working in this particular field. However, a philosophical question does arise. Is the problem of publication of exponentially increasing scientific effort to be solved by increasing fragmentation of journal content? The specialist interest in each of us approves but generalist interest regrets.

The background for *Infrared Physics* is understandable. The application of infrared radiation to chemical measurements has been established for some time and there exist various journals for such publication. The application of infrared to the measurement of physical properties of matter has had a recent, very rapid development under military sponsorship. The technical content, the security problem, and the general isolationist aspect of applied military endeavor brought forth a scientific group with no natural outlets for personal communication or publication. *Infrared Information Symposia* (*IRIS*) was created to meet the first need, and *Infrared Physics*, the second. It is hard to decide whether such narrowly defined creations are basic or not; time will tell.

With regard to the journal itself, the editorial approach is attractive. The articles in the first issue deal with basic infrared questions—some concerned with specific apparatus and some of a review nature. The geographical contribution and an article in German accent an international intent. The lead article, a short biography of Sir William Herschel, is a pleasant browsing supplement to the primary content.

Van Zandt Williams

* The Publishers do not state the frequency of issuance.

Optics of Thin Films. By Antonin Vasicek. Interscience, New York, 1959. 440 pp. $12.50.

The English edition of this book is described as a "reworked and supplemented edition" of the original Czech version. The extent of the added material is, in fact, extremely limited, even allowing for some delay in transmission of western information. The author does not claim that the book is a complete survey of the optics of thin films, but rather that it presents "problems which the author regards as important . . . and particularly those on which he himself has worked." It is stated that matters concerning measurement and applications of thin films will form the contents of another book, which one awaits with interest. Even so, a chief objection to the title of the present work would be

that it inevitably does suggest a more comprehensive coverage than is in fact given.

After a useful introductory chapter in which the relevant parts of Maxwell's electromagnetic theory are collected and presented in a very clear fashion, the treatment of films begins. Every step of the derivations of formulas for the optical properties of films is included and sometimes more than one method of derivation is given. While this minimizes the effort required of the reader, the rate of acquiring information is somewhat slow, as may be gathered from the fact that no less than 98 pages are devoted to the case of the single film.

Many methods of generalizing to the treatment of multiple films are given. Somewhat pointlessly, complete details are given of an early incorrect derivation (euphemistically referred to as "approximate"). Useful sections are included on achromatization of, for example, antireflecting systems, together with a very sketchy treatment of high-reflecting systems, and on interference filters.

The book forms, as is its intention, a good survey and history of much of the early work on films in optics. It is admirably produced.

O. S. Heavens

Books Received

Reviews will appear in subsequent issues of some of these titles.

Physical Chemistry, by F. Daniels and R. A. Alberty; Wiley, New York. 2nd edition, February 1961

Space Astrophysics, ed. W. Liller; McGraw-Hill, New York. 1961

Source Book in Astronomy 1900–1950, ed. H. Shapley; Harvard Univ. Press, 1960

Computing Methods and the Phase Problem on X-Ray Crystal Analysis, ed. R. Pepinsky, J. M. Robertson, and J. C. Speakman; Pergamon Press, New York, 1961

Temperature Measurement Engineering, by H. D. Baker, E. A. Ryder, and N. H. Baker; Wiley, New York. Vol. 2, July 1961

Fundamentals of Photographic Theory, by T. H. James and G. C. Higgins; Morgan and Morgan, New York. Revised edition 1960

Infrared Absorption of Inorganic Substances, by K. E. Lawson; Reinhold, New York, May 1961

Encyclopedic Dictionary of Physics, ed. J. Thewlis; Pergamon Press, New York, 1961. Vol. 1—A to Compensated Bars

Radiometric Standards and Measurements, by E. J. Gillham; HMSO, London, 1961

Information Processing, Butterworth, Washington, D.C., 1960

The Structure of Glass, Consultants Bureau, New York. Vol. 2, 1960

Careers in Physics, by A. W. Smith and W. L. Hole; Long's, Columbus, Ohio, 1960

Tools of the Astronomer, by G. R. Miczaika and W. M. Sinton; Harvard Univ. Press, 1961

Flammenphotometrie, by R. Herrmann and C. Th. J. Alkemade; Springer-Verlag, Berlin, 1960

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Meeting Reports

Atomic Spectroscopy Symposium, Argonne National Laboratory, June 7–9, 1961

Reported by Mary E. Warga, O.S.A., and University of Pittsburgh

On June 7, 8, and 9, 1961, the National Research Council Committee on Line Spectra of the Elements and the Argonne National Laboratory co-sponsored an Atomic Spectroscopy Symposium at the Argonne National Laboratory in Argonne, Illinois. It was a comparatively leisurely meeting (a rarity these days), and international in character, with representatives from six European countries in attendance and presenting papers. Approximately forty papers were given with plenty of time for discussion. The topics ranged from the status of atomic laboratory spectra, solar spectra, descriptions of lines of complex spectra such as rare earths, new transuranic elements and highly ionized, stripped elements, to hot plasma sources of excitation of spectra, line shapes, isotopes, hyperfine structure, optical masers, and instrumentation, stressing the use of interferometers and high speed electronic computing methods, especially in spectral line identification and classification.

Perhaps two factors stood out in the meeting: The first was the fact that, in this age of some de-emphasis in the teaching of optics and spectroscopy in many physics departments, in spite of an urgent need for scientists in this field, there seems to be a vital and continued interest in optical spectra at the present time, especially at government laboratories like Argonne, Los Alamos, and of course at the Bureau of Standards, as well as at a few university laboratories such as the Radiation Laboratories in Berkeley, California. The lively interest and contributions of our European colleagues in these areas is also most encouraging and worthy of note. Secondly, the introduction of high resolution methods, especially using the interferometer, and of high-speed computing machines, such as are used at the CNRS in Bellevue, France, are speeding up observations and calculations of many needed atomic energy levels—tasks which were formidable by previous, more tedious methods.

This was a very stimulating meeting for an atomic spectroscopist.

July 1961 Paris and London Meetings Sponsored by the International Commission for Optics

Reported by W. Lewis Hyde, J. W. Fecker, Inc.

The International Commission for Optics gives its blessing every year to one or two meetings on special topics organized by national committees. This year one meeting was held on July 5–8 in Paris (Optical Materials) and another on July 11–14 in London (Optical Instruments and Techniques).

By diligently flogging the membership of the OSA, our Assistant Secretary signed up 86 people for a charter flight, and, to the surprise of everyone, they all showed up on time July 3 at Idlewild, members, wives, and innumerable children. It looked at first as if the flight might be a bit crowded and uncomfortable, but all pain soon disappeared dissolved in BOAC hospitality.

The Paris meeting was devoted to "The Materials of Optics," and covered crystals, glass, thin films, and testing. Many of the papers will be printed in *Optica Acta*, and no attempt will be made here to abstract them. One very pleasant session was held at the beautiful new building of Saint-Gobain, the largest French maker of glass, and included a delicious lunch. On one night the delegates were entertained at a banquet distinguished by the

quality of the food and the brevity of the speeches. Other nights were devoted to a boat ride on the Seine, and a visit to the Opera.

The London meeting had sessions on instruments, optical design techniques, image formation, instruments for rockets and satellites, production and testing of components, and masers. The proceedings will be published as a book by Chapman and Hall. The sessions were held in the *highly* air-conditioned physics building at Imperial College, and, to accommodate the crowd, were relayed by television to a second hall. The delegates also had the pleasure of hearing Dr. H. H. Hopkins receive the Thomas Young Award and speak on "The Application of Frequency Response Techniques in Optics." Later that evening The Royal Microscopical Society received the foreign visitors at a soirée where old and new microscopes were on display.

H. H. Hopkins, *Imperial College*, and the author enjoying the Paris meeting.

Photo F. S. Harris

The delegates subsequently dispersed all over Europe for two weeks before gathering in London on August 1 for the return flight. Many of the families bought or rented cars and camping equipment and camped out. The charter flight and camping sufficiently reduce the cost to make family trips to Europe feasible and pleasant, even with small children. OSA members should already be considering this for next year when the ICO meets in Munich on August 19–26 and a similar charter flight will be arranged.

The Optical "Institutes" in Paris, Stockholm, Madrid, and Florence, and the "Departments" in London and Delft, treat optics as a unity in a way which we do here only at Rochester. As a result, European meetings are always stimulating to Americans working in optics, and these meetings were typical. The survey papers, the results of recent work by students, the practical studies arising out of industrial problems, and the theoretical papers were interesting and important. But best of all were the personal contacts with men and women of different training, different talents, and different experience.

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Sixth Annual Meeting of the Society of Photographic Instrumentation Engineers, Los Angeles, California, August 6–11, 1961

Reported by Lewis Larmore, Lockheed—California

The rapid expansion of the number of devices and the increased interest in photo-optical instrumentation dictated a growth in the duration of the August 1961 meetings of the Society of Photographic Instrumentation Engineers. Almost two thousand registrants participated in the five-day session which encompassed 32 technical sessions plus equipment exhibits presented by 51 companies. Continued enlargement of the society's meetings will strain even the spacious facilities of the Ambassador Hotel in Los Angeles which has provided accommodations for the past two SPIE national meetings.

If a single topic in a meeting of this kind may be highlighted, perhaps the interest shown in fiber optics should receive first place. The phenomenal growth of both theory and application of fiber optics has provided the photographic instrumentation fraternity a new tool within a period of about two years. In the 1959 meetings of SPIE only casual mention and some preliminary observations appeared on the program. By 1960 the theory had advanced to a point where application seemed imminent and a few strands of material appeared at the exhibits. The 1961 meetings devoted one complete afternoon to the subject and no less than eight companies displayed fiber optics to the participants. In addition, suggestions for potential uses of fiber optics permeated the discussion periods throughout the technical symposium. The current applications of fiber optics represent another of the interesting examples in which a scientific principle has awaited the advance in some technology before it can be put to general use.

Three other topics attracted unusual attention from the participants. Neither lasers nor optical correlation techniques had been previously discussed at an SPIE national meeting, but image intensification is a subject whose inherent capabilities were reasonably well known. While laser technology has made tremendous strides during the past year, these devices are not quite ready to be engineered into photo-optical equipment. This status was reflected by the absence of any operating laser in the exhibits, although a demonstration of a ruby laser was provided during the technical symposium. During the 1962 meeting we may expect to see these devices included in the exhibits. Optical correlation techniques have been used for several years, but only during the past few years have devices been widely explored for uses other than pattern recognition or map matching. Two papers on optical correlation covered new applications utilizing photographic memory techniques. Image intensifiers were represented at both the technical symposium and the equipment exhibits. In particular, a paper comparing the properties of image amplification with photography gave an insight for the evaluation of the two processes which should prove valuable to equipment designers.

In addition to these new and highly advanced topics the technical symposium presented discussions of a number of interesting photographic and optical problems. Included in the program were papers on data reduction techniques, tracking systems, fast shutters, new films, rapid processing, and the traditional workshop on extraterrestrial optical instrumentation requirements. In many instances the exhibitors showed hardware whose characteristics were presented at the technical symposium.

At its annual meeting the board of directors changed the name of the society to the Society of Photo-Optical Instrumentation Engineers but retained the same SPIE initials. The general chairman, Mr. Bernard Benson, and his staff as well as the officers of the society are to be congratulated for the high quality

of the technical symposium, the interesting exhibits, and the efficiency which penetrated the whole convention. For 1962 the SPIE Seventh Annual Technical Symposium and Exhiborama of Equipment will be held at The Biltmore Hotel in New York City during the week 6–10 August.

The 12th Annual Symposium on Spectroscopy, Chicago, Illinois, May 15–18, 1961

Reported by Marvin Margoshes, National Bureau of Standards, Washington, D.C.

More than 400 spectroscopists gathered in Chicago in mid-May to attend the 12th Annual Symposium on Spectroscopy. The meeting featured a well-rounded program of 40 contributed papers on x-ray, optical emission, infrared, Raman, ultraviolet absorption, and magnetic resonance spectroscopy, in addition to a number of invited speakers and clinics. As has been usual at these Symposia, ample discussion time was included in the planning for the program, adding considerably to the value of the meeting. Two sessions were held simultaneously.

A major portion of the program—14 papers, two invited seminars, and a panel discussion—was concerned with x-ray fluorescence spectroscopy. M. L. Salmon discussed some methods he employs for rapid processing of large numbers of samples. A rapid-scanning technique is used for preliminary surveys to select those samples which are of particular interest. Adequate resolution and reproducibility for the purpose are obtained at a scanning speed of 8° (2θ)/min when a recorder with a 0.6-sec response time is employed. Samples selected as a result of the preliminary survey may be analyzed by the standard techniques or by a semiquantitative method using finely ground samples spread out in a thin film between two layers of Mylar.

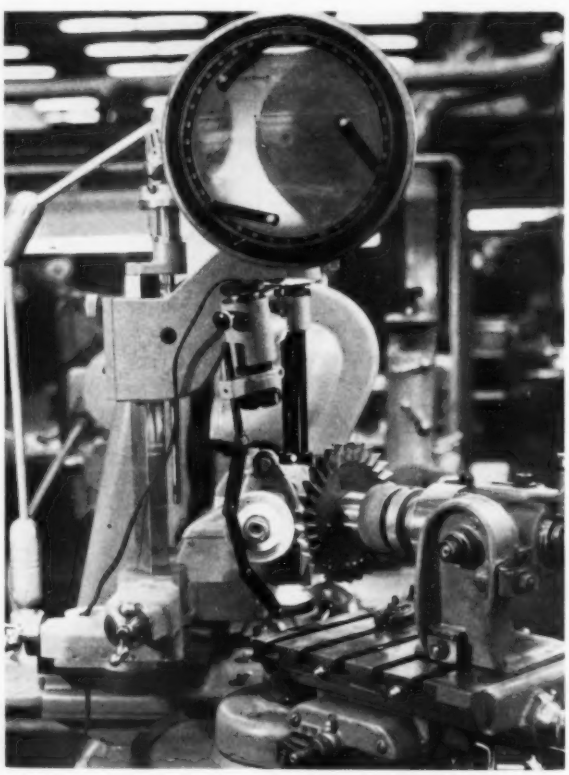
Several other presentations were concerned with the extension of x-ray fluorescence spectroscopy to lower concentrations of impurities, a topic of increasing importance to analysts. K. F. J. Heinrich presented a seminar on this subject, in which he considered a number of factors which must be taken into account when the best possible sensitivity is required. These included counting statistics, instrument noise and stability, background, and the preparation of samples and standards. J. Thatcher, J. Brown, and W. J. Campbell described the results of their studies on the application of x-ray fluorescence to trace analysis. With care in the selection of operating conditions, impurities in metals, oxides, solutions, or minerals could be detected at concentrations as low as 0.1 to 100 ppm, depending on the element being determined and the matrix. Elements which had been preconcentrated and spread into a thin film would be detected in amounts of 0.01 to 1 μg. W. R. Kiley also considered some instrumental factors in x-ray trace analysis, including the selection and operation of the x-ray tube and the choice of crystals.

In emission spectroscopy, there was a lively interest in the mechanisms of sampling and excitation in discharges. R. F. Majkowski and B. W. Joseph have studied the spectra of spark discharges with a time-resolution system similar to that of Bardocz. For an oscillating discharge between dissimilar electrodes, they have observed the lines of the ions from each electrode to oscillate in intensity at the frequency of the spark, but 180° out of phase. The lines observed at any moment are of the elements of the electrode that is the cathode. This is taken as evidence for sputtering as an important mechanism by which material from the cathode is introduced into the spark gap. The seminar presented by R. N. Kniseley was also concerned with sampling and excitation, particularly in discharges in controlled atmospheres. In one of the studies he described, comparisons were made of the rate of consumption of the sample by the discharge in various atmospheres. Here too, there was evidence for sputtering as an important process for the volatilization of materials in spark discharges. The discussion of these two papers and related matters was continued during the Optical Emission Problem Clinic, which followed the seminar.

The topic of excitation was further considered in a paper by L. E. Owen on a gas-stabilized arc discharge for the analysis of solutions and for the isotopic analysis of uranium hexafluoride gas. With the source adapted to UF_6 analysis, 0.038% U^{235} in U^{238} has been detected, and coefficients of variation of 1% or less have been obtained with a signal-to-background ratio of 1.1:1. The source for the analysis of solutions also promises to provide improved analytical precision.

The pattern of conferences on analytical spectroscopy has evolved into a few meetings of national or international scope, supplemented by regional meetings. The 12th Annual Symposium on Spectroscopy was sponsored by five sections of the Society for Applied Spectroscopy as a mid-Western regional meeting. It demonstrated that such conferences, with smaller attendance and more limited programs, can maintain a high quality of discussion and can usefully supplement the larger, less leisurely, national meetings.

Optical Activities in Industry



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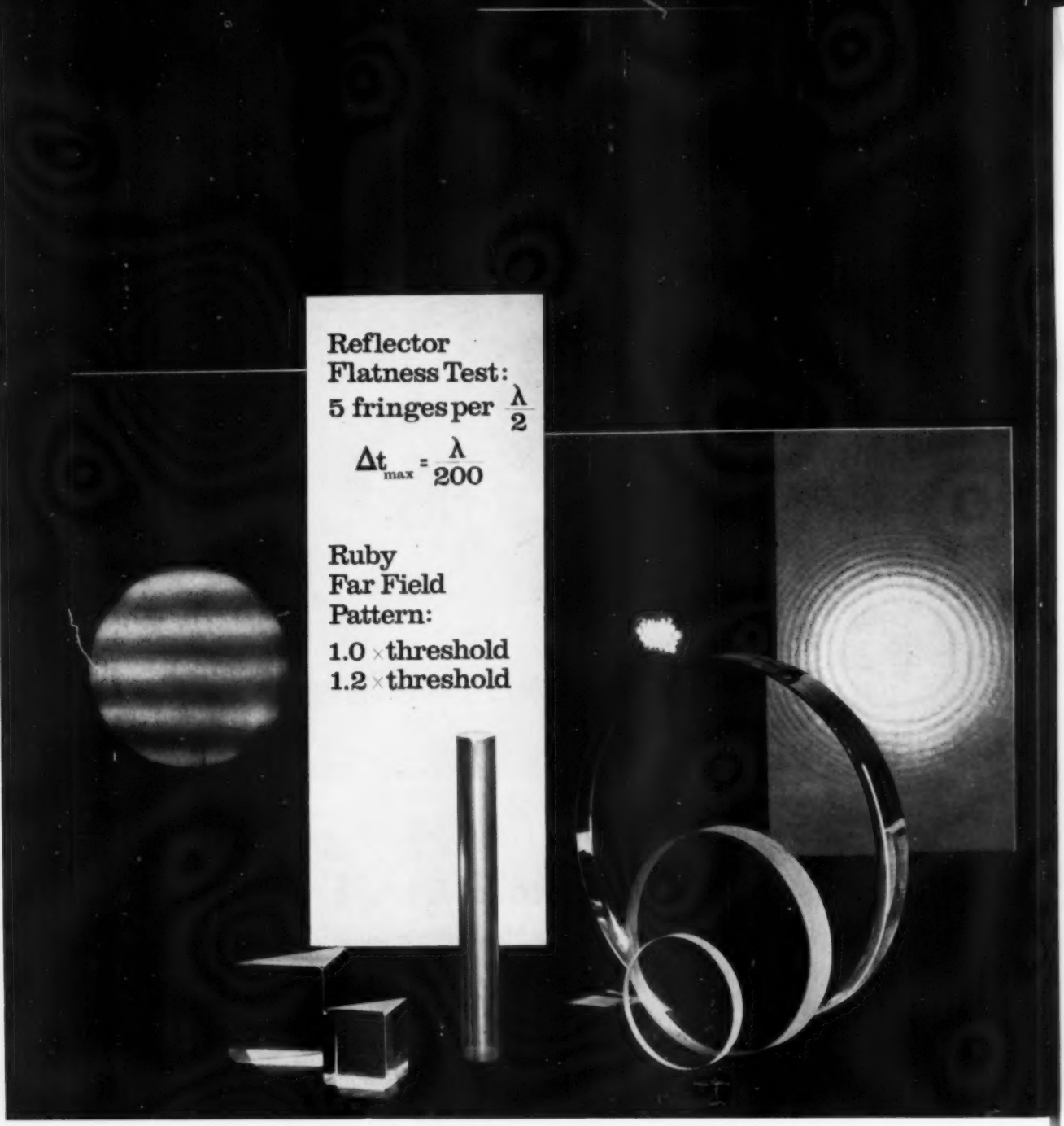

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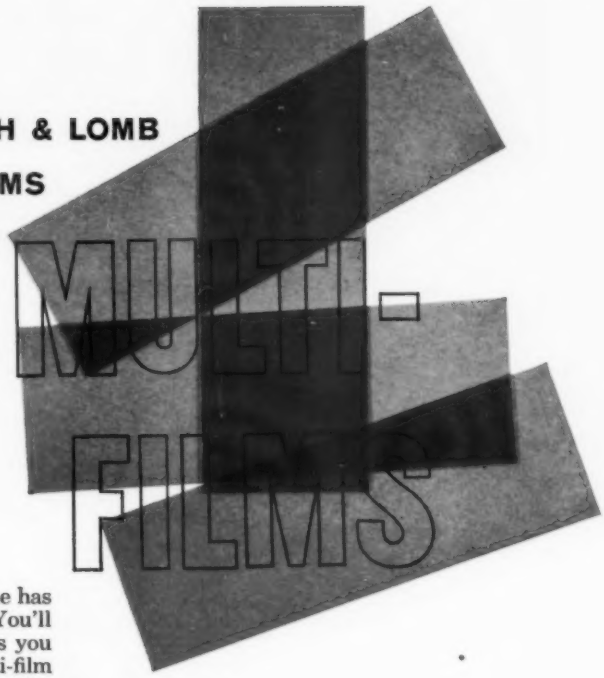

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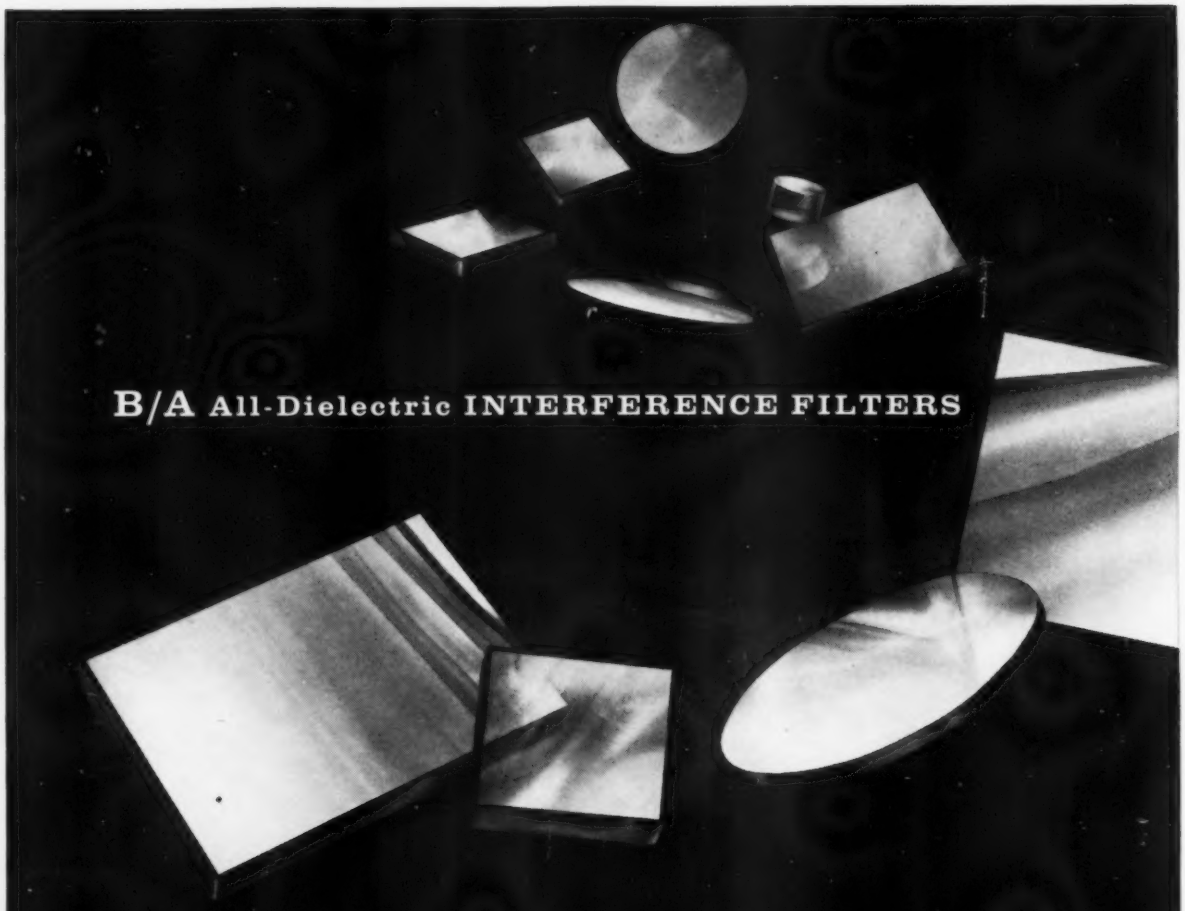

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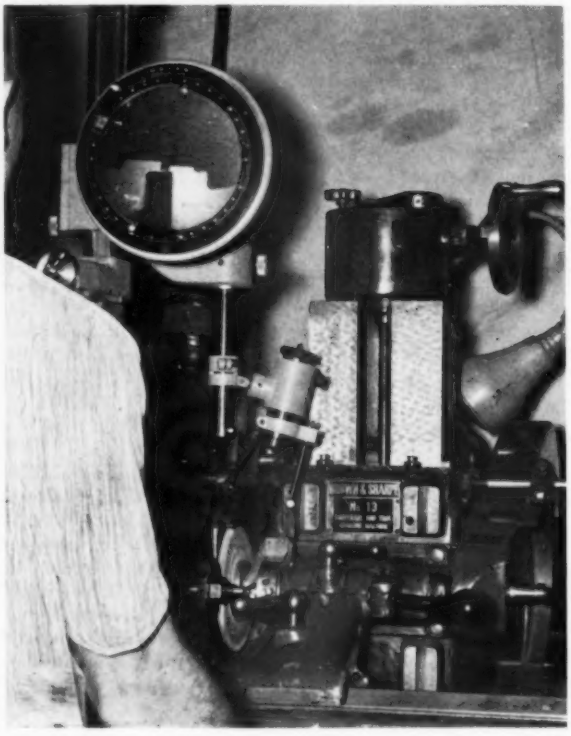
Applied Optics

Optical Activities in Industry

reported by FRANK COOKE, 66 Summer Street, North Brookfield, Mass.
Mr. Cooke welcomes news and comments for this column which should be sent to him at the above address

In this column and some to follow your scribe will indicate some practical uses of "Optics" in Industry. Since, by training and persuasion he is an optical worker and not a theoretical savant, the column must deal with things immediate and practical. We shall leave the realms of theory to our more erudite friends.

Probably at no time has there been such an extensive and pragmatic wedding of the optical and mechanical sciences. A few years ago *American Machinist* carried few references to optical techniques; now there are many. A case in point is the **testing of surface plates.** Numerous accurate machine shops now test and calibrate their reference planes or plates by moving a reflective surface about on the plate's surface, and watching the returning image's movement in an autocollimator. Formerly this checking was done by using master straight edges, covered with a thin coat of transferable-on-contact colored paste. This, rubbed on the plate, reveals the high and low spots. However, its accuracy is constantly suspect because of everlasting doubt about the master's flatness. Here the use of a collimator precludes this doubt. Since the use of large plane surfaces has always been, and is becoming more, important, we may bless the autocollimator for making them more accurate.



A new feature of our old friend the stationary **Optical Comparator** is its lighter frame and portability. It can be readily attached to various machines where accurate positioning of a tool to its work is essential.

Note the illustration showing the **milling cutter being ground.** Here a definite radius is needed on the cutting edges. Generally these radii are checked by using counterpart templates, of necessity a one to one ratio as to size and shape. Even a careful operator using this technique may fail to detect that "WHISPER" of light which indicates nonconformity. But, as we see, the greatly magnified image dispels doubt as to size and shape.

Your scribe has used this optical method in dressing a concave parabolic shape into a large grinding wheel of a cylindrical grinder. Then by moving a slowly turning glass blank into this wheel, a quite accurate convex surface was rough ground. A second finer grit wheel made the surface so smooth and accurate that it could be polished direct with no further preparation.

Observe the **cylindrical grinder being used to form a hard steel roll.** The shape desired can be placed on the viewing screen and the operator can manipulate his controls to form the same in his work. Since the ratio is many times to one, the shape is remarkably accurate. Imagine the problem of doing this with a hand held magnifier and a template!

The familiar engine lathe assumes another new function when the operator is able to see the enlarged image as he cuts. The illustration shows a **convex form turned on the end of a steel plunger.** Such curves can be held to an accuracy of 0.0002 cm per cm and better.

Problems—would Omar Khayyam have equipped his potter's wheel with an Optical Comparator? As he observed "A hair they say divides the false and true." And in today's machining standards less than a hair's diameter makes for success or failure. But then, Omar-Khayyam was speaking philosophically!

continued on p. 35

Applied Optics

Optical Activities in the Universities

reported by STANLEY S. BALLARD, Department of Physics, University of Florida, Gainesville, Florida. Professor Ballard hopes to receive news and comments for this column, which should be sent to him at the above address

A knowledgeable reader might be tempted to make the following somewhat sarcastic comments regarding the name of this column: "*What* optical activities?" and "In *what* universities?" His points would be well taken, since in this country optics is a field of academic physics which has gone out of style, along with acoustics and perhaps some other classical fields. In fact, in the U.S.A. there is only one school where a full and proper curriculum in pure and applied optics is given at both the undergraduate and the graduate levels; I refer of course to the University of Rochester's Institute of Optics. To be sure, there are a few other schools where graduate training can be obtained in physics with a research specialty in optics, such as Johns Hopkins University (John Strong) and the Pennsylvania State University (David H. Rank). And one may still do graduate work in such specialized optics fields as spectroscopy; for instance, at the Ohio State University.

Most undergraduate curricula in physics now include only a semester or perhaps a full year of optics on the intermediate level—say a level set by the popular textbook by Jenkins and White, and in some schools there is still an intermediate optics laboratory. In many schools this course in intermediate optics is required of physics majors, but in some it is not, and the latter trend is growing. The situation is even worse in graduate schools, where very few universities indeed offer an advanced course in theoretical optics. The standard course in electromagnetic theory often gives a brief theoretical treatment of certain optical phenomena, and this is as much pure optics as a graduate student is likely to get. (An exception would be what I call "quantum optics," but many prefer to include this material within the realm of modern physics or atomic physics.) These comments naturally raise the question as to where one obtains graduate training in theoretical optics other than at the University of Rochester. The answer is given by the fact that many of the people now working in the U.S.A. in advanced optics were trained at one of the excellent institutes or departments of optics in Europe.

The situation for *applied* optics is even more sad, from the academic point of view. Here there is a growing demand for trained workers, as the readers of this new journal realize very well. But few are the colleges which give any courses at all in the applications of optics, optical instruments, infrared instrumentation and the like. Thus people with a basic training in physics or engineering must learn their applied optics on the job—an admittedly inefficient and time-consuming process. The very facts of the appearance of this new journal and the enthusiastic acceptance which it appears to be receiving indicate again the great interest in applied optics in its broadest extent. Some data compilations, such as those conducted by the American Institute of Physics, show that a surprisingly large fraction of working physicists identify themselves with optics, and yet I say again that our facilities for training people in these techniques are ludicrously inadequate.

It is pleasant to note, in the "misery loves company" motif, that the unhappy situation re academic optics is being viewed with alarm by an increasing number of people. At least two groups of opticists have formulated definite proposals aimed to probe and improve the situation, and these groups have submitted suggestions to the Board of Directors of the Optical Society of America. One group proposes that the OSA arrange a survey on optical education. Such a survey would be carefully prepared so that the following type of questions could be dealt with on an action basis: What is the present and projected national need for men trained in optics? What are the detailed requirements of optical education? What programs now exist for providing such education, and are they adequate? The survey would also deal with questions having to do with attracting students into the field of optics during their collegiate years. It is a fact well-known to us physics professors that students' interests follow the styles (or perhaps help set them), so that whereas spectroscopy was popular in the 1920's, it was dramatically supplanted by nuclear physics, which in turn is giving way to solid state physics in the popularity contest. Unless we are able to convince students of the interesting career that optics promises, we cannot get them to take optics courses even though such courses are offered. This is another problem of which the officers and directors of the Optical Society of America are keenly aware. The second proposal is for the establishment of a national institute of modern optics in the U.S.A., roughly parallel to some of the other nationally supported research institutes now existing or being set up, for instance in the fields of nuclear physics, astronomy and atmospheric research.

It is too soon to go into detail on these proposals, especially since the Board of Directors of the OSA has not yet had adequate time to study them. You can plan on hearing more about them, both in this column and elsewhere, and your comments and suggestions will always be welcome.

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continued from opposite page

infrared spectroscopy comprise the joint researches of these two men .... **Dudley Williams,** Ohio State, is working this year with Marcel Migeotte at the University of Liège in Belgium, where atmospheric infrared absorption is being studied .... **Shigeo Minami** of Osaka University's Department of Applied Physics spent about three months at Ohio State University last year participating in the infrared research program. Dr. Minami had previously been awarded one of the three years' OSA memberships given through the American Institute of Physics .... **Randolph A. Becker,** who was formerly with the White Sands Missile Test Center for ten years, is now with the Jet Propulsion Laboratory in Pasadena as a Senior Research Scientist .... **Thomas P. Hunter** has joined the Optic-Electronic Corporation. Prior to this move, he had been with Texas Instruments for some ten years where he was, at various times, head of the optical model shop and sustaining engineer for the optics production shop. Mr. Hunter developed techniques for polishing and coating, for testing aspheric surfaces, and for manufacture using certain exotic materials, and he helped design, prepare, and test interference filters in the 0.4 to 15.0 micron range .... **Claud N. Bain** has

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Applied Optics

Of Optics and Opticists

This column is compiled partly from information sent by our Reporters in various centers of optics across the continent, but the Managing Editor welcomes news from any source

"The time has come," the Walrus said,
"To talk of many things:
Of shoes—and ships—and sealing wax—
Of cabbages—and kings—
And why the sea is boiling hot—
And whether pigs have wings." *Lewis Carroll*

Congratulations! . . . . to the Editor of the *Journal of the Optical Society of America*, **Deane B. Judd,** the outstanding authority on color in the U.S.A., who has been awarded the Illuminating Engineering Society's Gold Medal for 1961. Dr. Judd is the U.S. Representative to the International Commission on Illumination's Committee on Colorimetry and Chairman of the C.I.E. International Committee of Experts on Colorimetry. He is also President of the Munsell Color Foundation, and presently in charge of the colorimetry group of the National Bureau of Standards . . . . to **Warren L. Rhodes,** Editor of the *I.S.C.C. Newsletter*, first Rochester resident to win R.I.T.'s Statistical Quality Control Award . . . . to our own Editor, **John N. Howard,** on his appointment to serve on a Planning Task Force of some 150 scientists, responding to a request initiated by the President's Special Assistant for Science and Technology, to recommend goals and outline a national plan for the atmospheric sciences over the next ten years . . . . to **Ralph M. Evans,** Director of the Color Technology Division of the Eastman Kodak Company, who has been named recipient of the Herbert T. Kalmus Gold Medal Award of the Society of Motion Picture and Television Engineers . . . . to **Deane R. White,** Associate Research Laboratory Director with Dupont-Parlin, N.J., elected SMPTE Engineering Vice President . . . . to **Mary Warga,** OSA Executive Secretary, **E. D. McAlister,** OSA Director, and **John N. Howard** who celebrate birthdays next month . . . . to **Kathryn McCarthy,** appointed acting Chairman of Tufts University Physics Department during Professor Knipp's sabbatical . . . . to **Henry O'Bryan,** appointed scientific assistant to the vice president engineering and research, Bendix Corporation, in Washington . . . . to **Alex G. Smith,** professor of physics at the University of Florida, who has been appointed Assistant Dean of the U.F. Graduate School. He will divide his time between Graduate School activities, and teaching and research in the Physics Department. Dr. Smith is a Director of the Association of Universities for Research in Astronomy, Inc. (AURA, the governing body of the Kitt Peak National Observatory), and is a member of the Scientific Advisory Committee for the U.S. Navy's new 183 m (600-ft) radio telescope installation at Sugar Grove, W.Va. . . . to **Robert S. Quackenbush, Jr., U.S.N. (retd.)** who was honored by the Fellowship Award of the Society of Photographic Scientists and Engineers for his early work in the field of aerial photography and interpretation. Admiral Quackenbush is now a special technical representative for the Polaroid Corporation. . . . to **Frank C. Back,** president of Zoomar, who was also made a Fellow of SPSE at this time. . . . to **Dave MacAdam,** President of OSA, and **Fred Perrin,** who have just celebrated twenty-five years with Kodak. . . . to **Richard S. Hunter** who has received an ASTM Award of Merit in recognition of significant contributions to the evaluation of optical and appearance properties of materials, particularly in Committee E-12 on Appearance. . . . to **Cyril J. Staud,** Vice-President and Director of Research of the Eastman Kodak Company, who has been named recipient of the Progress Model of the Society of Motion Picture and Television Engineers for his continued outstanding technical contributions to the engineering phases of the motion picture and television industries. . . . and to **Walter S. Baird** for achieving the fame of appearing on *Today!*

Edward L. O'Neill, Associate Professor of Physics at Boston University, is spending one year at M.I.T. Research Laboratory of Electronics where he has been appointed Guest of the Institute . . . . **Wolfgang Franzen,** formerly of the Arthur D. Little Company, has joined the Department of Physics at Boston University as Associate Professor of Physics, with particular interests in optical pumping . . . . **John S. Christie, Jr.,** formerly an engineer with Proctor and Schwartz of Philadelphia, has joined the Hunter Associates Laboratory, McLean, Virginia . . . . **David M. Gates** has been appointed editor of Section D, Radio Propagation, of the *Journal of Research of the U.S. National Bureau of Standards.* He succeeds Dr. James R. Wait who has been editor of Radio Propagation for the past two years. Dr. Gates is the consultant to the Director of Boulder Laboratories of the National Bureau of Standards in the Physics of the Atmosphere Division of Central Radio Propagation Laboratories. Previously he had been the scientific director of the London Branch of the U.S. Office of Naval Research . . . . Two of the civilian members serving on the newly established Scientific Advisory Council of the H.Q. Office of Aerospace Research of the U.S. Air Force are **Yoshio Tanaka,** authority on ultraviolet spectroscopy, and **Hans Hinterreger,** authority on the chemical structure of the upper atmosphere . . . . **Paul E. Weber** has joined Trion Instruments Inc. of Ann Arbor, Mich., as senior scientist participating in optical laser development . . . . **Donald S. Lowe** of the Bendix Systems Division has been promoted to Head of the Infrared and Optics Department . . . . **Lloyd G. Mundie,** *Space Optics* feature editor for the March issue, has moved from Bendix Systems Division to work with **Lewis Larmore** as head of the new Lockheed Laboratory to be located in Rye Canyon . . . . **D. J. Lovell,** formerly of Bendix, has received an appointment at the University of Michigan Institute of Science and Technology . . . . **R. P. Madden** has joined the staff of the Atomic Physics Division of the National Bureau of Standards, to develop a line of research which will form a sound foundation for the development of absolute radiation standards for the far ultraviolet spectral region. In addition to research on sources and detectors, the interaction of far ultraviolet radiation with materials will be investigated. Dr. Madden was formerly Chief of the Spectroscopy Section of the ERDL Physics Research Laboratory . . . . **George W. Stroke,** who has worked on the development of the interferometric control of grating ruling with George R. Harrison at M.I.T. since 1952, returned last year from an eighteen month stay at the Sorbonne and the Institut d'Optique in Paris and was appointed Lecturer in the Electrical Engineering Department at M.I.T. . . . . **Ely E. Bell,** Ohio State, is spending the present academic year with Ludwig Genzel at the University of Freiburg in Germany. Various aspects of far

continued on opposite page

From the Editor

At long last *Applied Optics* has become a reality . . . but the labors of launching this journal have been greatly alleviated by the enthusiasm of everyone we asked to help: feature editors, column and geographic reporters, reviewers, referees. All of these have responded with cheerful willingness. But most heartening of all has been the response from contributors because this has justified our belief that such a publication is needed. Papers started to come in last May and have continued to do so in an overwhelming but very welcome stream. The featured subject of our first issue has doubtless helped; optical pumping is a new and exciting area of optics: yet many of the authors who have had papers accepted for publication herein are publishing their work for the first time in an OSA journal. We want them to stay with us and to bring their friends. One of the aims of *Applied Optics* is to bring (back) together the many workers in the fringe fields of optics who have no real publishing home.

Part of each issue will be devoted to the feature subject *but only part;* we emphasize this because, perhaps, our original publicity did not make sufficiently clear that *each* issue would contain papers in *any* of the broad areas of applied optics, in disciplines related to optics and employing optical techniques, *as well* as in the featured subject. It is our intention that a topic will be introduced in each issue and highlighted by a review (the lead) article. A feature editor for each topic will become a part of our repertoire.

Let us be the first to admit that this first issue is not a good example of our intentions! So many papers were submitted on optical pumping, and they were so timely, that we decided to give pride of place to them in January. Even so, we have as many optical maser papers again ready for publication, and these will appear in the forthcoming numbers.

Your Editor is new at the game of editing; he will probably make many mistakes. He is painfully aware of the deficiencies in his own knowledge of optics and he hopes to lean on many other people for help and advice. He is also not particularly trained or disposed to write bi-monthly sermons in this space; he may yield it occasionally to a Feature Editor of greater wisdom. The experiences of the past year of organizing this journal and debating its why and wherefore have uncovered a variety of possible topics for future editorials. Let us mention a few, so that you may communicate your sentiments to us about them, if you will:

Our first and primary concern is that we do not infringe on the domain of our sister publication the *Journal of the Optical Society of America*. And before we say anything further we want to express to Deane B. Judd, Editor of *J. Opt. Soc. Am.*, a sincere appreciation of all he has done over the past few months to help the birth of *Applied Optics*, in the form of including a section in his *Journal*, comments on his editorial page, his suggestions to authors re publishing in *Applied Optics*, and his helpful advice on many points that were new to us. We do not think it out of context here to say a word of thanks to Wallace R. Brode, President of OSA last year; this journal has benefited from his long experience as the Editor of *J. Opt. Soc. Am.* and the advice and active help he gave us during 1961. When we first drew up a tentative scope for this journal, we included all aspects of applied optics, including physiological optics, but when we polled the membership of the Society in July 1960 the one (and only) substantial group that was cool or indifferent to the idea of a second journal was the color-vision-physiological category. Since the Editor of *J. Opt. Soc. Am.* himself is a color man we have more or less resolved that we would make no incursions in that area but would concentrate on making *Applied Optics* a home for those optical papers that had been appearing in journals of other disciplines. Our feeling is that, after a few issues, our character will emerge, and then we shall be able to find our proper modus vivendi with *J. Opt. Soc. Am.* Dr. Judd has stated his point of view clearly in the October 1961 issue of *J. Opt. Soc. Am.*

Our next concern is our relationships with our cousin journals within the American Institute of Physics' family, and also with other standard journals. Another question is how international should a national society's publication be; how large should be the proportion of articles in foreign languages, particularly Russian—and it must not be forgotten that communication is a two-way process; we want foreign workers to read *Applied Optics* as much as we want to read their work. Should such foreign-language papers be kept to a minimum, such as an occasional fine meal in a foreign restaurant, or should we make an effort to welcome them all? Should we attempt to impose "correct" terminology on our contributors, as the Editor of *J. Opt. Soc. Am.* has been trying to do? Readers will notice that we prefer authors to use the metric system. Can we accept review, historical, or tutorial articles in other than the featured subject and remain an original-content journal? Your comments concerning these matters or any features or departments that you particularly like or dislike will be much appreciated.

JOHN N. HOWARD

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Applied Optics Patents

It is hoped to make this column a regular feature before long, somewhat along the lines of R. W. Young's patents reviews in the *Journal of the Acoustical Society of America* . . . we should be remiss not to take this opportunity to thank Dr. Young for all his advice. We have in mind a panel of some ten or more volunteers, each of whom will review patents being published in his area of optics. This panel will work under the direction of a chairman or Patents Editor who will coordinate their activities and prepare the reviews for bimonthly publication in *Applied Optics*. Readers who are interested in helping us make this Patents column a reality should write to the Managing Editor—they will be welcomed.

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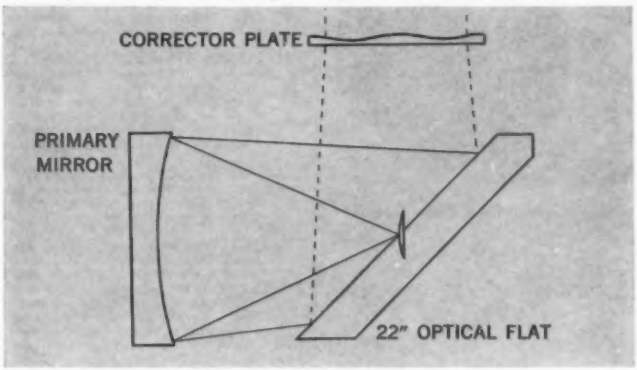

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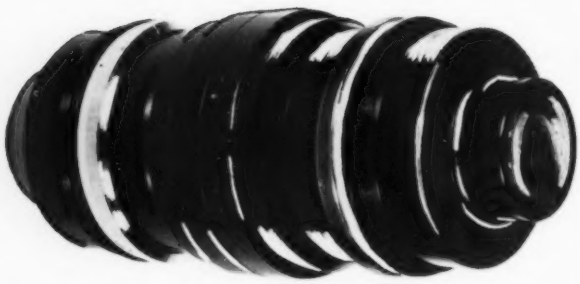

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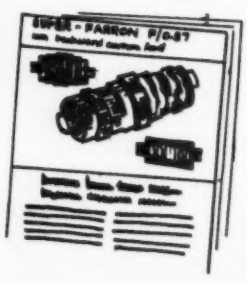

ASO CORPORATION MEMBERS

continued from page 32

E. I. DUPONT DE NEMOURS AND COMPANY, INC., Flint Laboratory, St. John and Hamilton Streets, Flint, Michigan, *provides technical support for the sale of DuPont paint products to the automotive industry. Specialized skills in the important sciences related to this area of finishes application are concentrated in a professional staff composed principally of physicists, chemists, and engineers. The Laboratory includes a well-equipped facility for measurement, specification, and control of color and other appearance attributes of organic finishes.*

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EDMUND SCIENTIFIC CORPORATION, Barrington, New Jersey, *is an optical and science mail-order house, supplying optics to research centers, university and industrial laboratories, and educational institutions. Edmund has a stock of war surplus optical parts and items, most adaptable to many present-day uses. Edmund offers telescopes, microscopes, binoculars, and industrial magnifiers and optical measuring devices, including the lowest-priced American-made stereo microscope. Edmund offers lenses—achromatic; convex, concave, menisus, etc., prisms of all types—right angle, porro, amici roof, dove rhomboidal, leman, etc., plus many science learning and teaching aids.*

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ELGEET OPTICAL COMPANY, INC., 838 Smith Street, Rochester, New York, *fabricates lens assemblies, optical instruments and systems from the initial design stages through engineering, prototype production, and the ultimate completed unit.*

EPPLEY LABORATORY, INC., 12 Sheffield Avenue, Newport, Rhode Island, *was founded in 1916 for the purpose of manufacturing standard cells, and other products were developed: precision dc measuring instruments, thermopiles of various types, and the Eppley pyrheliometer for the measurement of total solar and sky radiation. After the Second World War interest in thermal detectors continued with the production of the Golay pneumatic infrared detector. Recently, Eppley has enlarged its line of pyrheliometric equipment and also offers certain calibration facilities in the thermal radiation field.*

FAIRCHILD CAMERA AND INSTRUMENT CORPORATION, Syosset, New York, *in the past forty years has developed its capabilities in optics, electronics, and mechanics. Of eleven divisions, four have concentrated in the field of optical engineering: Defense Products Division designs and manufactures optical systems and subsystems for the military and is engaged in basic research. Graphic Equipment Division is a pioneer in optical applications for the graphic arts industry. Du Mont Division provides specialized optical instruments for the military, industry, and commerce. Industrial Products Division produces and distributes cameras and optical instruments.*

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continued on page A21

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continued on page A22

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LINK DIVISION GENERAL PRECISION, INC., Binghamton, New York, *is the originator of flight simulator training equipment and the only commercial manufacturer of automatic interferometric measuring instruments in the world. Examples are the FRINGECOUNT Micrometer for measuring length, the GONIMET for measuring angles, and the Automated High Accuracy Coordinate Measuring Equipment for photogrammetric coordinate measurements.*

NORTRONICS DIVISION OF NORTHROP CORPORATION, 500, East Orangethorpe Avenue, Anaheim, California, *was established to handle Northrop's growing activities in the development and manufacture of military optical, electronics and mechanical systems and components. Nortronics now has four departments, one of which, Systems Support, is the center of optical research, engineering, and manufacturing; other departments also have optical groups active in their own specialized fields. The areas of Nortronics' optical interests include: fire control instruments, special cameras, infrared systems, electro-optical devices, navigational systems, projection viewers, and other reconnaissance and photogrammetric instruments.*

OPTICS TECHNOLOGY, INC., 248 Harbor Boulevard, Belmont, California, *is engaged in contract research, systems development, and manufacturing. Research talent is active in the area of fiber optics and non-classical optics. Systems work includes both components development and systems analysis and design. Manufacturing includes the production of thin film interference filters, fiber optics devices, and analytical and process control instrumentation.*

OPTISCHE INDUSTRIE "DE OUDE DELFT," Postbus 72, Delft, Holland, *although founded as recently as 1939, are makers of high-precision optical and electronic instruments of their own design e.g. a special night camera for filming scenes exclusively illuminated by moonlight; etc. Production plants are located in Delft and Leeuwarden in the Netherlands; marketing and sales are on an international level, backed by a central staff in Delft with technically-trained, world-traveling delegates. "De Oude Delft" has subsidiaries in the U.S.A., France, Germany, and the Netherlands.*

OPTOVAC, INC., East Brookfield Road, North Brookfield, Massachusetts, *specializes in the production of optical crystals grown from the melt, with particular emphasis on high quality optical calcium fluoride (fluorite), but also of sodium chloride, potassium bromide, potassium chloride, and other inorganic crystals. The company also is producing high quality optical maser crystals.*

OWENS-ILLINOIS, 1700 N. Westwood, Toledo, Ohio, *manufactures many products made from plastics, paper, and glass. The Technical Center at Toledo houses most of the Company's technical effort, which includes fundamental research broadly related to the fields of polymers and plastics, paper forest products, and glass and silicate chemistry, in addition to applied research, development and engineering related to specific products.*

PACIFIC UNIVERSAL PRODUCTS CORPORATION, 168 Vista Avenue, Pasadena, California. *Facilities include metallic coatings, Schlieren wind tunnel mirrors, low reflection coatings, plate glass requirements to tight tolerances, magnesium fluoride coatings, gold coatings, camera lens coating and repairs, binocular lens coating and collimation, aluminizing and fabrication of telescope mirrors to $\frac{1}{10}$ wave with protective silicon monoxide overcoating, etched or photo reticles and metal depositions of patterns on glass.*

PERKIN-ELMER CORPORATION, Norwalk, Connecticut, *was founded in 1937 as a source of precision optics and optical design in the United States. Since that time, the company has produced high performance optical systems, and has entered several new fields. It is actively engaged in the development of electronic-optical systems for space and defense programs, and is one of the leaders in the fields of laboratory and process control instrumentation. The company also produces a line of precision electronic components.*

PITTSBURGH PLATE GLASS COMPANY, Glass Research Center, Box 11472, Pittsburgh 38, Pennsylvania, *was founded in 1883 and today is a leading manufacturer of flat glass, chemicals, paints, brushes, and fiber glass. In 1914 the Company entered the optical glass field and since has been a supplier to the optical instrument and ophthalmic industries of an ever broadening assortment of products. Pittsburgh Plate Glass Company makes optical, filter, and polished glasses for instrument makers and a complete line of glasses and pressings for ophthalmic lens manufacturers.*

POLAROID CORPORATION, Cambridge, Massachusetts, *is engaged in research, development, and manufacture of products involving the interaction of light and matter, with special emphasis on light polarizing filters and their applications, and on the cameras and films employing the one-step photographic process to produce finished pictures immediately after exposure.*

SAWYER RESEARCH PRODUCTS, INC., 35400 Lakeland Boulevard, Eastlake, Ohio, *was founded in 1956 to produce commercial products by hydrothermal growth techniques, of which cultured quartz was the first. Licensed under Western Electric Company and Clevite Corporation patents, the Company drew mainly on results and experience in growing quartz gained in a research and development program that had been progressing continuously since 1945 at the Brush Development Company (later a division of Clevite) with financial support from the U.S. Signal Corps.*

SCIENTIFIC OPTICAL CORPORATION, 215 South Irwindale Avenue, Azusa, California, *produces high quality precision optics, creating components and devices for a multitude of industrial applications. CETRON, a leader in the field of electronic tubes and light control devices, recently merged its engineering capabilities with those of Scientific Optical.*

SIMPSON OPTICAL MANUFACTURING COMPANY, Chicago, Illinois, *serves the military, the machine tool, and the photographic industry, as well as marketing direct reading, high precision VERNAC measuring instruments. In addition to high precision lenses for optical tooling instruments, surveying equipment, television and motion picture cameras and projectors, Simpson produces reticles, employing the latest evaporation coating techniques. The Simpson engineering staff are experts in design of complete optical systems, and the Company maintains an optical laboratory in support of its research and development programs.*

SPACE TECHNOLOGY LABORATORIES, INC., Los Angeles 45, California, *as an industrial contractor to the Air Force, Army, NASA and other government agencies and industrial companies, performs research, development, engineering, fabrication and testing in missile and space programs. STL employs more than 4000 persons, of whom more than 1700 are scientists and engineers, in the performance of over 80 current contracts and subcontracts. STL, through its Products Division, manufactures technical devices developed from its company-sponsored space technology research.*

TE COMPANY, 1221 Chapala Street, Santa Barbara, California, *is engaged in optical design and development, and in the production of custom optics. Industry and government are sponsoring Te work in areas including: optical payloads for satellite and space applications; missile and anti-missile sensing elements; battlefield optical aids; airborne reconnaissance and surveillance systems. Company facilities include a computer center, optical grinding and polishing shop, electronics laboratory, and precision optical assembly and test laboratory.*

TIFFEN OPTICAL COMPANY, 71 Jane Street, Roslyn Heights, New York, *manufactures photographic filters and optical accessories for industrial and scientific use. Tiffen has complete facilities for modern vacuum coating, an advanced color laboratory, and manufactures optical components from prototype to mass production. It specializes in grinding, edging, drilling, and polishing all types of glass. Tiffen has a modern metal working machine shop with multi-spindle automatics which go up to 10 cm diameter, as well as completely equipped tool rooms and secondary machines.*

TINSLEY LABORATORIES INC., 2448 6th Street, Berkeley 10, California, *was founded in 1926. It is engaged in the design and manufacture of precision optical components and optical instruments. These include missile and satellite components, special cameras, data acquisition equipment, tracking and astronomical telescopes.*

TROPEL, INC., 52, West Avenue, Fairport, New York, *is concerned with optical engineering and consulting. Activities are divided between the production of advanced optical designs, together with the development of computing methods, and the manufacture of special instrumentation including prototypes. Commercial instruments manufactured are vacuum ultraviolet monochromators and accessories, high-time resolution spectrographs, and UniSlide instrument slide units.*

UNITED LENS COMPANY, Southbridge, Massachusetts

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continued on page A24

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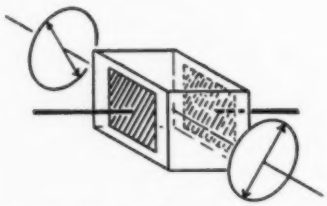

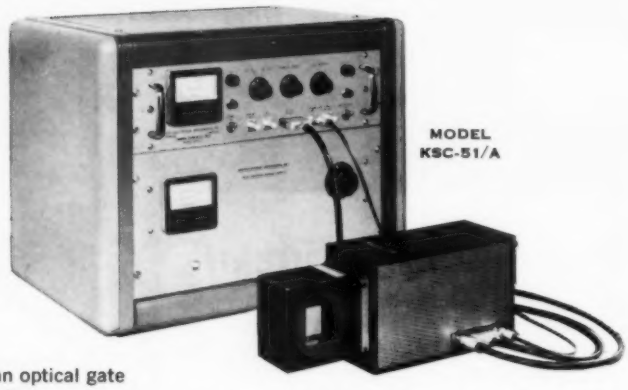

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OSA CORPORATION MEMBERS

continued from page A22

VALPEY CRYSTAL CORPORATION, 1244 Highland Street, Holliston, Massachusetts, *formed in 1931, fabricate crystalline and glass materials for the optical and radio-electronics fields. A wide range of services is available to meet the growing needs of the precision optics and special fabrications industries, and specially trained optical engineers and technicians, utilizing modern equipment, are available for all research, development, and production needs.*

VAN KEUREN COMPANY, 176 Waltham Street, Watertown, Massachusetts. *H. L. Van Keuren pioneered the use of monochromatic light with optical flats for testing flatness and parallelism, and he designed a unique micrometer using lightwaves which permitted all operators to use the same pressure. Modern grinding, lappings, and polishing skills allow production of precision pivots, seals, rings, and other custom work as well as catalog items which include a complete line of dimensional gauges.*

WHITE DEVELOPMENT CORPORATION, 80 Lincoln Avenue, Stamford, Connecticut

WOLLENSAK OPTICAL COMPANY, Rochester, New York, *has a complete line of 8 and 16 mm cine, TV professional 35 mm motion picture, still camera, wide-angle, telephoto, enlarging, portrait, and process lenses. Wollensak is the exclusive manufacturer in the U.S.A. of mirrotel lenses—lenses incorporating mirror optics, and in 1950 entered the field of high speed photography with a line of FASTAX cameras. The third segment of Wollensak business is the design, development, and manufacture of precision optical-electro-mechanical devices.*

XEROX CORPORATION, 6 Haloid Street, Rochester 3, New York, *manufactures and markets office copying equipment and supplies, photocopy equipment and supplies, and photographic sensitized materials. It specializes in xerography, a unique dry electronic process for copy reproduction, which is featured in the company's desk size 914 Office Copier. Principal plants are in Rochester and Webster, New York.*

ZOOMAR, INCORPORATED, 55 Sea Cliff Avenue, Glen Cove, New York, *pioneered in varifocal optics and other high precision optics of original design. Its products include: Zoomar lenses; space optics for missiles and satellites; microscopic equipment; Zoomfinder for U.S. Signal Corps; optics for gun cameras; training devices for U.S. Navy.*

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The Physics Department of the Aeronutronic Research Laboratory is well equipped for its work involving both contract and in-house research. Among the facilities are: a multiple-pass absorption cell in which paths up to one mile can be obtained with controlled atmosphere, pressure, and temperature; a furnace for measuring the high temperature emissivities of gases; a 100 x 25 foot infrared dark tunnel; and standard, high speed computing equipment.

Following is a partial list of basic and applied research areas where work is currently in progress at Aeronutronic:

- Refractive and reflective optical systems
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- High temperature emissivities
- Atmospheric absorption
- Target discrimination
- Molecular emission and absorption
- Satellite and space vehicle subsystems

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BEST WISHES

Ferson Optics, Inc. extends to the Optical Society of America its best wishes for success in a much-needed publications venture.

We expect the optical industry will profit immensely from sharing information on techniques and processes through this new medium as it has in the past from the dissemination of theoretical and research material through the pages of J.O.S.A.

It is our hope to be able to contribute in a small way from time to time to this endeavor.

We have enjoyed a measure of success in the field of optical instrumentation. We have specialized in problems involving *interferometry* and other techniques of precision measurement, but we are also fond of *astronomical telescopes* and *research accessories*, as well as complex periscopes of all sizes. We are experienced in the design and construction of *infra-red* and *spectrographic systems* and happy to be of assistance in any of the above areas.

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OPTICAL SOCIETY of AMERICA

SPRING MEETING—MARCH 14, 15, 16 & 17, 1962—WASHINGTON, D.C.
ANNOUNCEMENT OF PROGRAM AND REQUEST FOR CONTRIBUTED PAPERS

The Spring, 1962 meeting of the Optical Society of America in Washington will encompass a broad program including a two-day symposium on vision, invited papers on optical masers and on other subjects still being determined, plus an instrument exhibit.

INVITED PAPERS

The **two-day symposium on vision** on Wednesday and Thursday, March 14 and 15, will be co-sponsored by the Inter-Society Color Council, the Armed Forces Committee on Vision of the National Academy of Sciences, as well as by the Optical Society of America. It will comprise some fifteen invited papers on five major areas of physiological optics, in addition to which there will be five reviewers who will summarize the papers within these categories, viz.: microanatomy and biochemistry of the visual systems, electrophysiology of the visual system, retinal image formation, simple discriminatory functions, and contributions to color discrimination theory. This symposium will review the past ten years' work in each of these areas as well as look toward future developments.

Sessions on optical masers will start with an invited paper by Dr. Peter Franken of the University of Michigan on "Experiments Utilizing Optical Masers." It is hoped that this will engender many contributed papers to be presented in this area of optics. With the emphasis on optical masers at this meeting and the fact that optical pumping and masers is the featured subject of the January 1962 issue of APPLIED OPTICS, OSA hopes to become a home for scientists working in this area of optics.

An invited paper on another currently vital area of optics, as well as the name of the outstanding *after-dinner speaker at the banquet,* will be announced later.

INSTRUMENT EXHIBIT

So successful were the 1960 and the 1961 exhibits that one is planned for March 1962 stressing important developments in optical instrumentation. Companies should write for details to Dr. J. W. Gebhard, Applied Physics Laboratory, 8621 Georgia Avenue, Silver Spring, Maryland.

HOTELS

The headquarters hotel will be the Mayflower, Connecticut Avenue at La Salle Street. A room reservation card is enclosed. Rooms will also be available in the nearby Pick-Lee House, 15th and L Streets. Members should write directly to either hotel mentioning the Optical Society of America.

ABSTRACTS

Presentation of contributed papers will be limited to fifteen minutes, and the second and other papers of an author or co-authors on the same or similar subjects will be placed on a supplementary list of papers for presentation only if the program time permits. **ALL ABSTRACTS MUST BE SUBMITTED TO THE EXECUTIVE SECRETARY FOR ARRIVAL NO LATER THAN FRIDAY, JANUARY 5, 1962:**

Mary E. Warga, Executive Secretary
Optical Society of America
1155 Sixteenth Street N.W.
Washington 6, D.C.

OSA CHARTER FLIGHT TO EUROPE, AUGUST 1962

OSA hopes to arrange a charter flight to Europe for the month of August 1962, for *members* attending the Munich ICO Meeting August 20–25. We contemplate a flight leaving New York (Idlewild) on Monday, 30th July for Paris, and returning from Munich Airport on Monday, 27th August to New York. Members would make their own way between Paris and Munich. It is necessary to finalize applications for a plane within the next month so we need now an expression of interest (without commitment, of course) from members. Members who are interested in principle should return the bottom half of this page to the Executive Office as soon as possible. The round trip fare—New York–Paris Munich–New York—would be about $275.00 The dates are not final.

Some members have expressed interest in attending the Symposium on Electromagnetic Theory and Antennas, 25–30 June 1962 in COPENHAGEN. If it is possible to fill a plane (86 people), then OSA will organize another charter flight for 1962. Will any interested members please indicate accordingly on the form below. NO INTERCHANGE BETWEEN THIS JUNE FLIGHT AND THE LATER FLIGHT IN AUGUST WOULD BE POSSIBLE.

REPLY
Assistant Secretary
OPTICAL SOCIETY OF AMERICA
1155 Sixteenth Street N.W.
Washington 6, D.C.

CHARTER FLIGHT 1962

( ) I am interested in principle in a charter flight N.Y.–Paris Munich–N.Y., August 1962

( ) I am interested in a mid June–mid July New York–Copenhagen–New York charter flight 1962

Name.....Membership No.....

Address.....

.....

FUTURE MEETINGS

ROCHESTER, NEW YORK
October 3, 4, 5, 6, 1962

MANGER HOTEL
Details to be announced.

Information about later meetings will be announced shortly.

OPTICAL SOCIETY OF AMERICA
Executive Office
1155 16th Street N.W.
Washington 6, D.C.

Optics and Spectroscopy

OiS Club The Optical Society of America has been translating *Optika i Spektroskopiya* and distributing this monthly journal free—thanks to an NSF grant—to all OSA members and subscribers to the *Journal of the Optical Society of America*. This free distribution has been an experiment for three years, so that the individual reader might become accustomed to reading a translation journal not as an oddity but as a publication that is looked for each month in the same manner as is *J. Chem. Phys.*, *J. Am. Chem. Soc.*, etc. In December of this year the NSF grant ends, but the interest in *Optics and Spectroscopy* is now too lively for OSA to discontinue the translation, so they have evolved the OiS CLUB, a group of some twenty-three Societies whose members may subscribe to *OiS* at a reduced rate, viz: *ASA, AAPT, ACS, ACA, AOCS, APS, ASTM, Electrochemical Soc., IRDG-UK, IRIS, Inst. Chemists-India, Inst. Physics and Physical Soc-UK, ISA, I-SCC, Netherlands Chemical Soc., SAS, SSP, Soc. for Chem. Ind. UK, Chem. Inst. Canada, SPSE, PES group-UK, Soc. Anal. Chem.-UK, Can. Ass. Phys.*

OPTICS AND SPECTROSCOPY is the leading Russian journal in the field, its coverage corresponding in part to that of the *J. Opt. Soc. Am.*, although the spectroscopy papers are more theoretical than analytical or instrumental. Luminescence and optical properties of materials are fully represented, instrumental optics, diffraction and coherence problems less so.

OPTICS AND SPECTROSCOPY is published *monthly* in English translation 3 months after the Russian original e.g. the January 1962 issue will appear in March/April.

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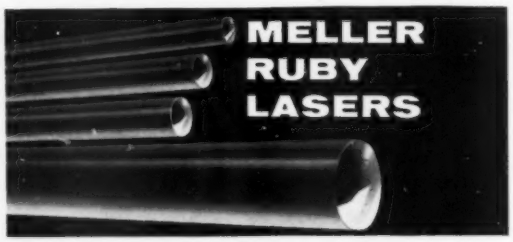

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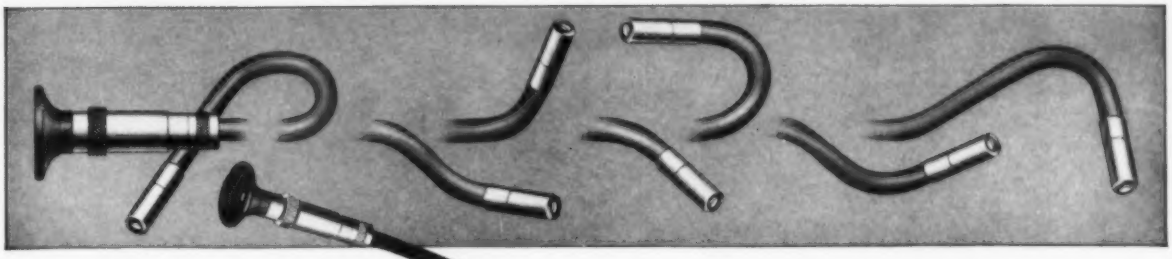

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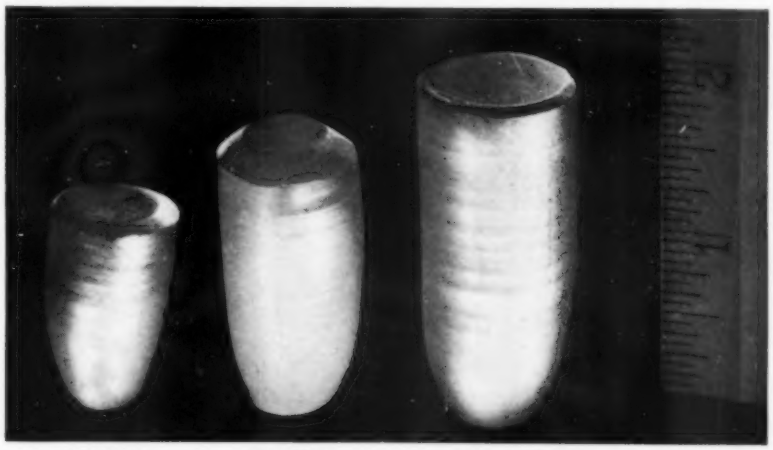

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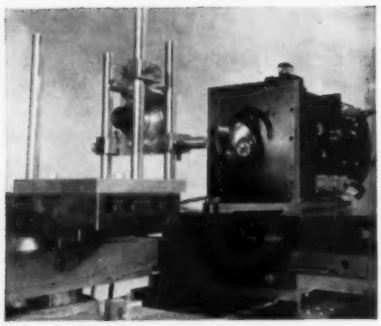
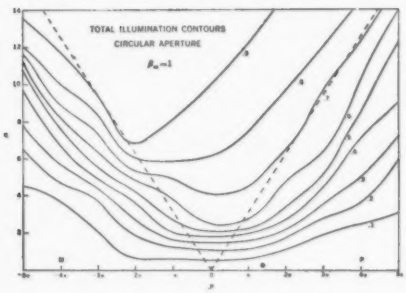
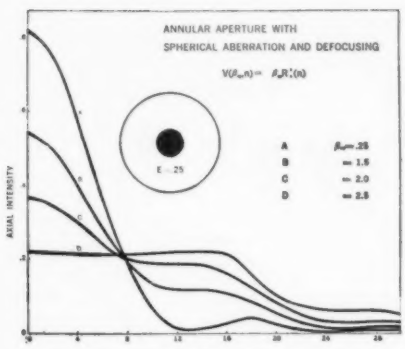


Sine Wave Analyzing Bench



Precision Optical Test Bench



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- Seismometers
- Spectrographs
- Spectrometers
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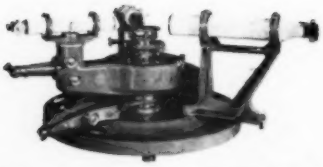
- X-ray Equipment



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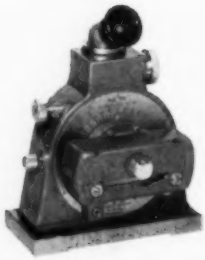

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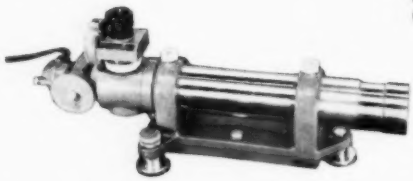

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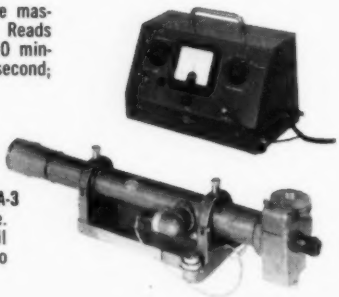

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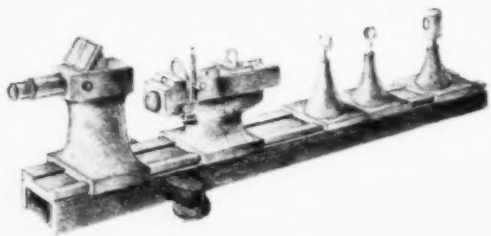

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